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AFFDL ltr, 31 May 1973

AD839441

AFFDL-TR-67-107
VOLUME I

QUANTITATIVE STRUCTURAL DESIGN CRITERIA BY STATISTICAL METHODS

VOLUME I. A CRITIQUE OF PRESENT AND PROPOSED APPROACHES TO STRUCTURAL DESIGN CRITERIA

INNES BOUTON

and

D. J. TRENT

TECHNICAL REPORT AFFDL-TR-67-107, VOLUME I

JUNE 1968

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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200 - August 1968 - CO455 - 46-989

QUANTITATIVE STRUCTURAL DESIGN CRITERIA BY STATISTICAL METHODS

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FOREWORD

This report was prepared by North American Rockwell Corporation for the Structures Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under Air Force Contract No. AF33(615)-3755, Project No. 1367, "Structural Design Criteria," Task No. 136714, "Structural Loads Criteria Simulation Techniques."

The study and analysis on which this report is based are work accomplished by the Methods and Criteria Unit of the Structures and Design Department in the Space Division of North American Rockwell during the period from April 1966 to May 1967. Mr. M. Fisk was Program Manager for North American Rockwell. Mr. George E. Muller of the AFFDL (FDTR) was the Project Engineer. Permission to reproduce a portion of the paper, "The Role of Informatics in Modern Flight Systems," by Professor C. S. Draper has been granted by the Journal of Spacecraft and Rockets.

The contractor's designation of this report is SID 67-495-1. This report was submitted by the authors in February 1968.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Francis J. Janik, Jr.
Chief, Theoretical Mechanics Branch
Structures Division
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ABSTRACT

Exploratory research, needed to develop quantitative structural design criteria for aerospace vehicles, has been conducted to relate the probabilistic nature of design, operational, and environmental experiences to the structural performance of aerospace vehicles. This design criteria is predicated on the concept of structural reliability. Volume I presents a critique of present and proposed approaches to structural design criteria. Volume II presents recommendations for a deterministic structural design criteria procedure based on statistical methods. This is a new procedure intended to overcome the problems associated with other structural design criteria procedures. The new procedure is demonstrated on the F-100 airplane by comparing the output of the computer program with actual service records. Volume III formulates two computer programs for the procedure and presents user's instructions for the programs.

The critique of Volume I concludes that none of the approaches in the literature today provides a satisfactory foundation for quantitative structural design criteria based on statistical methods.

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ILLUSTRATIONS

LIST OF SYMBOLS

ASIS	Actual State Information System
DSIS	Desired State Information System
MS	Margin of safety
SDC	Structural design criteria
γ_s	Coefficient of strength variation = $\frac{\sigma_s}{\mu_s}$
μ_s	Mean strength
σ_s	Standard deviation in strength

SECTION I

INTRODUCTION

The need to relate structural design criteria to structural reliability has been recognized for many years. For instance, Pugsley, in Reference 1, presented one of the earliest known discussions of the statistical approach to structural design. However, all past attempts at imposing a quantitative structural reliability requirement have been rejected by those most directly responsible for the structural design of operational vehicles.

Much of the previous work can be characterized by the naivete with which the structural reliability problem is approached. Most investigators confuse the ability to calculate the probability of failure when load and strength spectra are assumed to be known with the ability to determine the true structural reliability of an operational structural system. Part of the difficulty is that, when the problem is formulated in such a way that it can be solved rationally, it is often simplified to the point where the problem is no longer rational. Too often, procedures that appear to offer solutions to structural reliability problems are unworkable because they omit one or more of the basic elements of the problem. Procedures actually used in the design of aircraft, as exemplified by MIL-A-8860 and its predecessors, have included many such elements without explicit recognition. Thus, such elements are easily overlooked by those who are attempting to formulate solutions to structural reliability problems. It is believed that unsatisfactory experience with making radical changes in the method of solving a problem underlies much of the reluctance of practicing engineers to blithely adopt proposed new ideas.

In the case of statistical approaches to structural reliability, some of the considerations that appear to be overlooked are the fact that:

1. Errors or discrepancies often occur between the actual and the calculated spectra.
2. The powerful effect of testing as a means of disclosing errors is not fully exploited.
3. The necessity for a procedure for demonstrating proof of compliance with the requirements.
4. The requirement for assignment of responsibility for certain actions which are necessarily associated with any determination of structural reliability.

The study, described in the three volumes of this report, is intended to accomplish the exploratory research needed to develop quantitative structural design criteria for aerospace vehicles that will relate the probabilistic nature of design, operational, and environmental experiences to the structural performance. This design criteria is predicated on the concept of structural reliability. Volume I of the report presents an evaluation of existing and proposed approaches. Volume II presents the recommendations for a deterministic structural design criteria procedure based on statistical

methods. This is a new procedure intended to overcome the problems associated with other structural design criteria procedures. The new procedure is demonstrated on the F-100 airplane by comparing the output of the computer program with actual service records. Volume III formulates a computer program for the procedure and presents user's instructions for the program.

The first portion of the study, reported herein as Volume I, takes up the problem of evaluating the various approaches to structural design criteria in three major steps. The first of these steps is to develop a clear understanding of the various functions that contribute to a structural design system. This understanding is aided by extending the application of the concepts presented by Draper in Reference 2 to structural design systems. The purpose of any structural design system is the creation of an operational structural system that will enable the vehicle to satisfactorily perform its mission. When the contributions of the various functions comprising the structural design system are understood, better procedures can be established to fulfill these functions.

The second step is to evaluate two general structural design systems to determine how well they perform the functions established in the first step. One of these generalized systems is the Present (Factor of Safety) Structural Design System. This system represents the structural design procedures and the state of the art as it exists today. The other generalized system is a Purely Statistical Structural Reliability System. This represents a hypothetical system which establishes a structural reliability number as the basic requirement of the structural system. Standards for the evaluation of these two systems are established in this second step. These same standards become the basis for formulating the new procedure presented in Volume II of this report.

The third step is to evaluate a group of papers considered to be a representative cross section of the structural reliability methods extant in the technical literature. These papers are evaluated by the same standards used to evaluate the two generalized systems in the second step.

The identification of the desirable features together with the problems in the existing and proposed structural design systems as identified in this Volume I provides the basis for the development of a new system. This new system, described in Volumes II and III, will attempt to incorporate the desirable features and to overcome the problems as identified in Volume I.

SECTION II

UNDERSTANDING THE FUNCTIONS OF A STRUCTURAL DESIGN SYSTEM

2.1 INTRODUCTION

Publication of a paper by Professor C. Stark Draper of MIT has provided an intriguing new framework for developing a better understanding of the structural design problem. Draper's paper, "The Role of Informatics in Modern Flight Systems," was first presented as the 29th Wright Brothers Lecture.[2] Later it was published in the Journal of Spacecraft and Rockets. This paper has all of the earmarks of a classic. It is suggested as recommended reading for all knowledgeable structural engineers.

Although Draper's presentation is given in terms of stabilization and control systems for flight vehicles, his principles are universal. Draper himself points this out in the last paragraph of his paper. "It is important to note that the functional pattern discussed in the paper may be applied not only to flight vehicles but to operating systems of all kinds ranging from single human beings to industrial complexes, armies, and whole nations. Clear understanding of the functional relationships involved is surely a very useful factor in achieving optimal results from any system. The concepts discussed in the paper represent new concepts that surely will be helpful for the realization of this goal." It appears that an extension of Draper's concepts to the structural design system provides a perfect rationale for understanding what we are trying to do in structural design and why.

In the development of his informatics thesis, Draper starts with a discussion of the Wright Flyer. He points out that the "Wright brothers pioneered greatly in recognizing that the sensing, processing, and application of information to the control of the airframe and its propulsion system was not an incidental matter but really filled roles as essential as those played by wings, engine, propellers, and auxiliary surfaces." The airframe is essentially the structural system. It is apparent that the Wright brothers understood that control of the structural system was a vital part of the development of a good vehicle system. A specific instance of this understanding is their structural design criteria. As indicated by the quote in Reference 3, they established their objective as a structural system that would sustain five times the weight of the vehicle and they took steps to implement this objective. This present report will show how similar concepts can be applied to current structural design problems.

2.2 THE INFORMETICS CONCEPT

The discussion of the informatics concept is so well done in Draper's paper that it appears better to directly reproduce those parts of the original text that develop that concept rather than trying to rewrite Draper's words. This reproduction is with the permission of the Journal of Spacecraft and Rockets.

a. General Background

Environment for mankind is the total complex of all the things with which direct or indirect interactions may occur. In general, the environment is made up of so many factors that to consider all of them simultaneously is manifestly impossible. This means that, in dealing with activities directed toward producing desired interactions with the environment, some *region-of-interest* having a manageable size is selected and blocked out for concentrated attention. A region of this sort is suggested in Fig. 1 where the real-world situation of complete enclosure is shown by the somewhat amorphous boundaries. Any factors not singled out for special attention remain with the environment.

Figure 2 represents the situation when the region-of-interest is a conceptual operating system to supply interactions with the environment which are imagined to be desirable. Again, the environment completely surrounds the region-of-interest so that any inward drawn arrow represents an input, whereas any outward drawn arrow into the environment is an output. Thin arrows represent a flow of information, often in the form of signals, whereas broad arrows suggest relatively high power, great force, or considerable flow rates of materials. Intermediate width arrows would show intermediate levels. Any human activity toward the final realization of an operating system must begin with the imagination of desired results. With these results in mind, imagination should call up the concept of a proper *effector* to receive inputs from the environment and to generate the desired results. In Fig. 2, the initiating Imagination and Desires element is represented by a box in the lower left-hand corner of the region-of-interest, whereas the effector is shown with its environmental inputs and outputs in the upper right-hand corner of the region. Before significant results can be expected in practice, clearly defined functional operating chains must exist between the two boxes. In practice, the components that act as links in these chains will be different for each system considered, but it is always possible to identify two regions of distinctly different characteristics and a third region with the general nature of an interface. To clarify discussions, to provide general guide lines for drawing diagrams, and to stimulate advanced developments, the three fields that include all the elements of any operating system are as follows. 1) *Effectetics:* The art, science, engineering, and technology of realizing means for directly achieving *desired interactions with the environment;* 2) *Informetics:* The art, science, engineering, and technology of collecting and applying information to generate operating instructions for the realization of desired results; and 3) *Control (and Stabilization)* (Interface between Informetics and Effectetics): The art, science, engineering, and technology of receiving control commands generated by informetics and causing associated effectors to function in accordance with these commands.

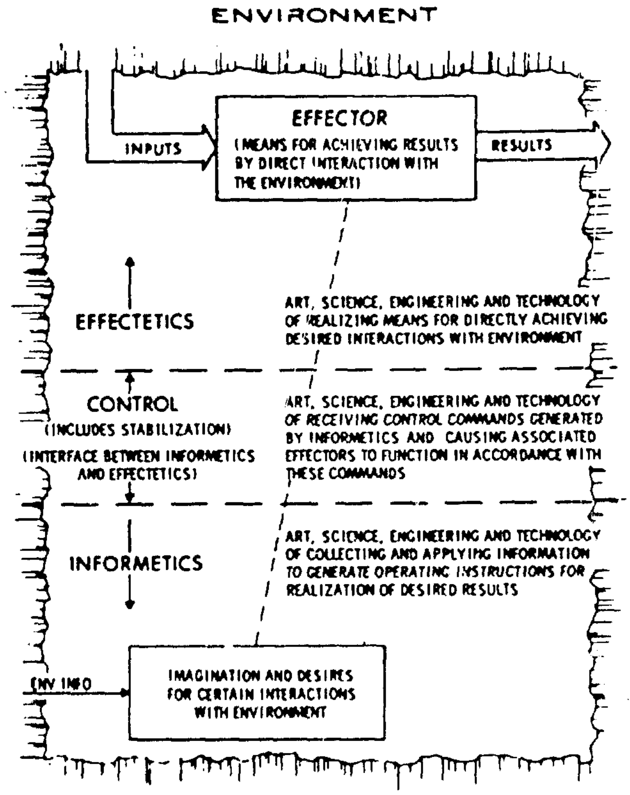


Fig. 2 Functional diagram for conceptual operating system to supply desired results.

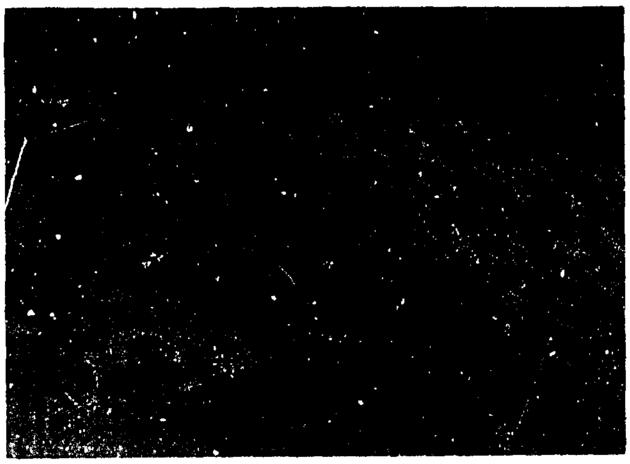


Fig. 1 Region of interest as a generalized concept.

Figure 3 represents the over-all complex of science and technology as a region of interest. Basic science, under the direction of scientists, receives support from the environment to deal with the natural laws and materials of nature and produces systematic and verified knowledge without concern for particular applications. Applied science deals with generalized applications of scientific knowledge, receiving

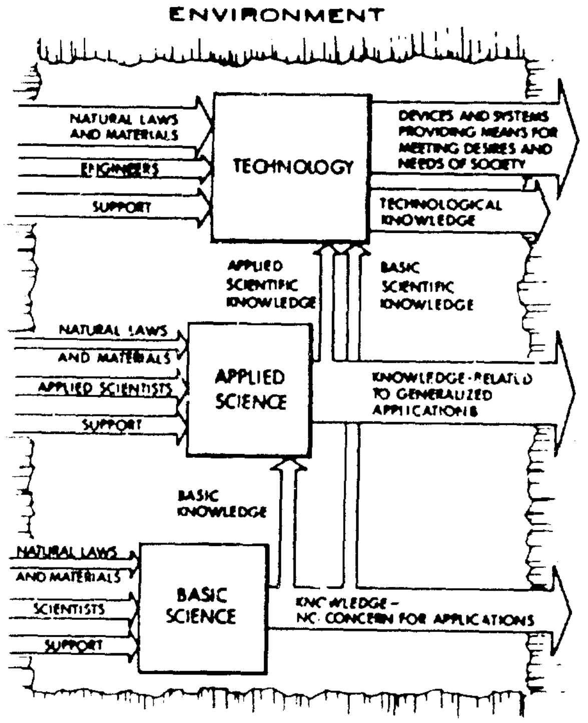


Fig. 3 Science and technology as a region of interest.

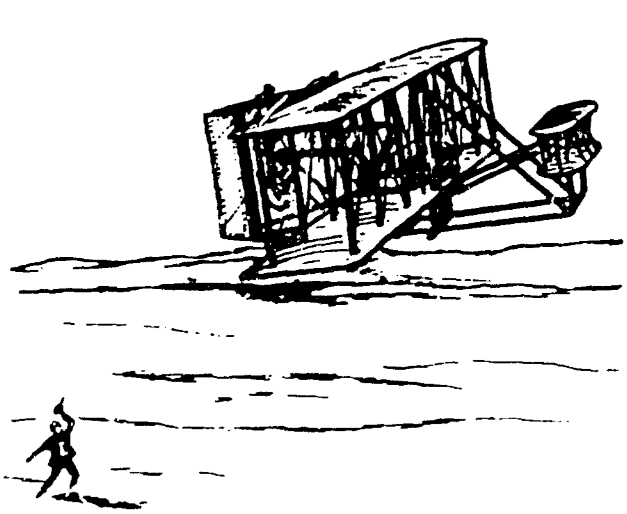


Fig. 4 The Wright Flyer.

support from the environment to deal with the laws and materials of nature under the direction of applied scientists. Technology receives knowledge from both basic and applied science, significant support and often considerable quantities of materials from the environment to generate devices and systems that operate as means for meeting the desires and needs of society. Technological knowledge is supplied to the environment as an incidental output. In general, engineers play roles of assuming over-all responsibility for the activities of technology in a way that corresponds to the positions accepted by scientists in their relationships with science.

Using the concepts illustrated by the figures, the Wright brothers treated their flyer as a project of technology with all phases, science, applied science, and engineering handled personally by themselves. A revolutionary feature of their approach was to deal with the circumstances of man-carrying flight in terms of a complete system with effectetics, informetics, and control integrated into a single pattern. In their time this was an unusual mental attitude since the usual procedure in dealing with flying machines was to concentrate on the effector with complete disregard of, or very little attention directed toward, the requirements of informetics. Experience with bicycles, unstable alone and beautifully stable and controllable in the hands of skilled riders, certainly guided the thoughts of Wilbur and Orville into channels that, with hindsight, we now know to have been extraordinarily productive.

It is the purpose of this paper to show how the development of informetics has been so fruitful for aeronautics and to

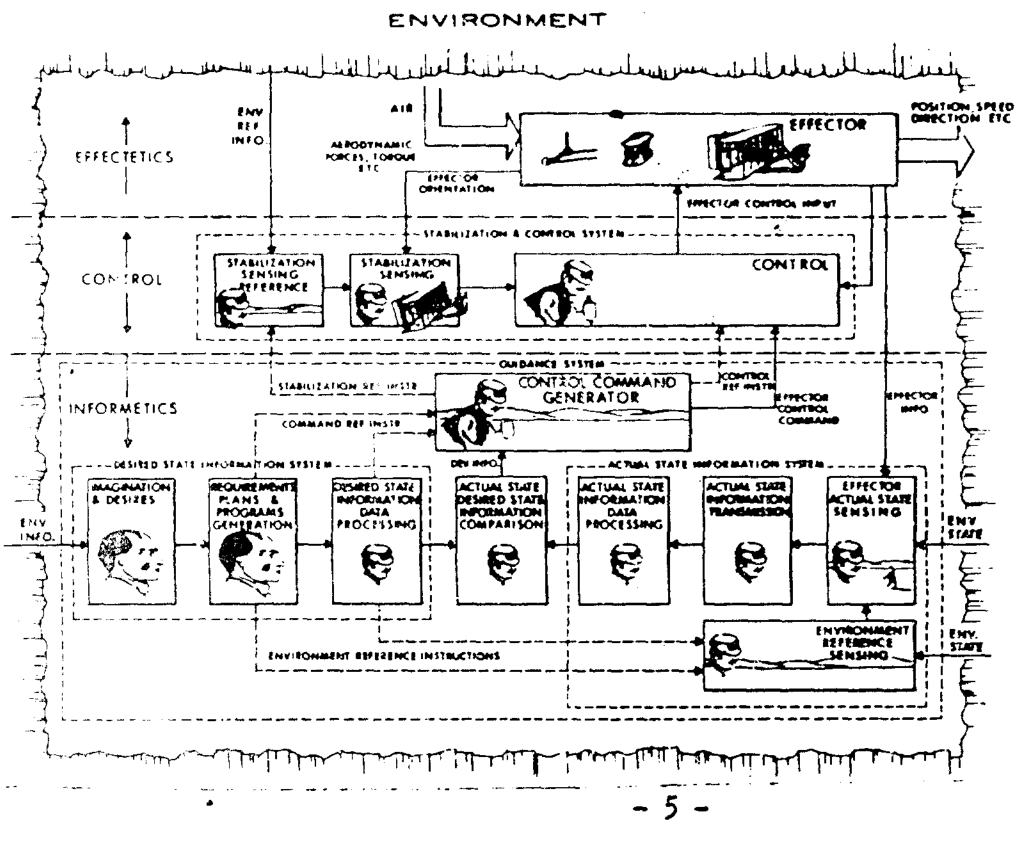


Fig. 5 Functional diagram for operation of the Wright Flyer.

suggest possibilities in which this relatively new field will lead technology to ever greater levels in the years ahead.

b. The Wright Flyer

Figure 4 represents the Wright Flyer above the sands at Kittyhawk. The reclining pilot warped the wings to give rolling actions by sideways motion of his hips to move a yoke, which also worked the vertical tail to compensate for yawing moments caused by roll. His left hand operated the elevator surfaces carried ahead of the wings to adjust climb and descent. With the Flyer ready to fly, but without a man in the cradle, effectetics had certainly done its job but without means to accept information and supply stabilization and control inputs to the airplane, and effective flight was impossible. Once a skilled pilot took his place at the controls the situation was entirely changed because the man complemented the inanimate effector by adding the previously missing elements of control and informetics. It is only a factual recognition of the exceedingly great contributions of a properly educated and trained human being to review briefly some of the essential functions he was capable of fulfilling under proper circumstances. These functions are noted in boxes for the functional diagram of Fig. 5 to indicate how the open spaces of Fig. 2 might be filled in to represent the interconnections between imagination and desires to a flying machine effector when all Control and Informetics functions come from a human pilot.

The first requirement on control system operation is Stabilization, which is the continuous maintenance of effector operation close to equilibrium conditions based on selected

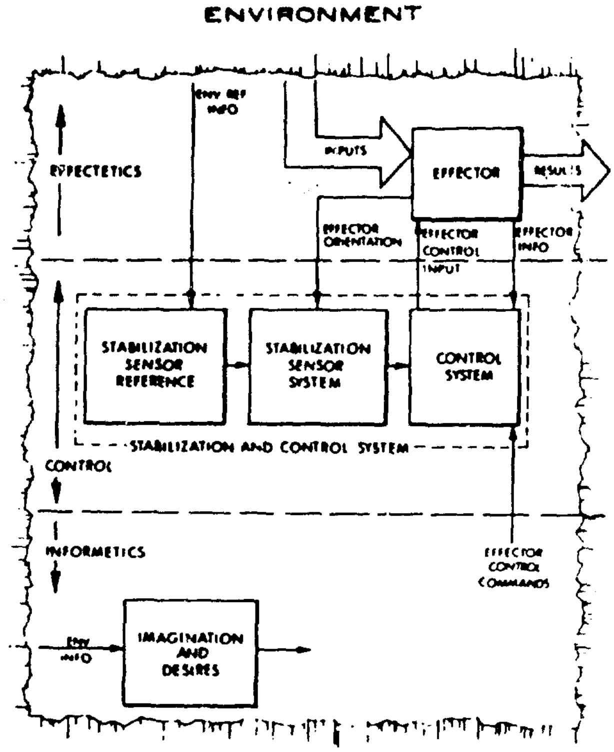
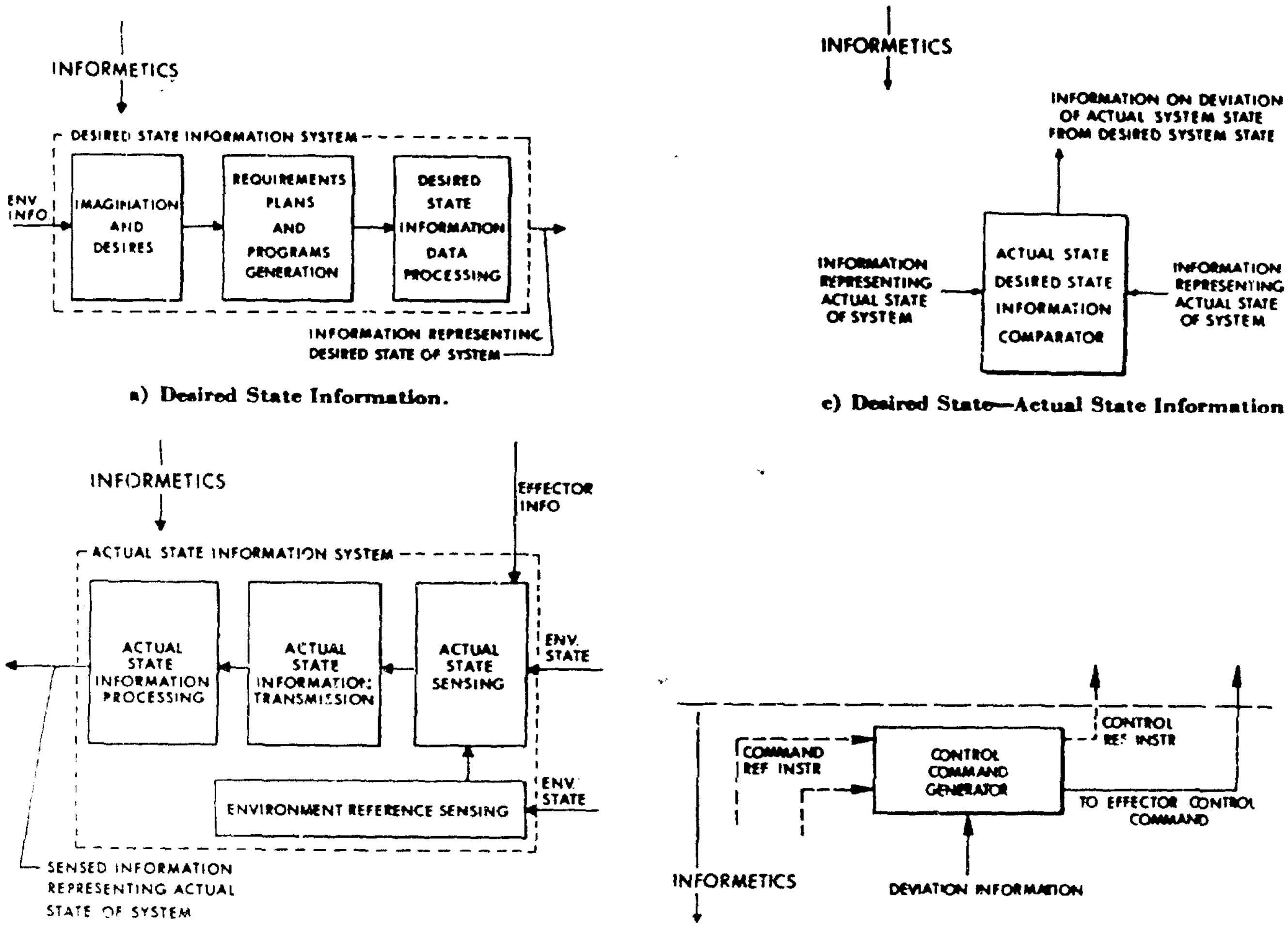


Fig. 6 Generalized functional diagram for stabilization and control.



a) Desired State Information.

c) Desired State—Actual State Information

b) Actual State Information System.

d) Control Command Generator.

Fig. 7 Variations upon informetics portion of Fig. 6 which lead to the over-all generalized functional diagram of Fig. 8.

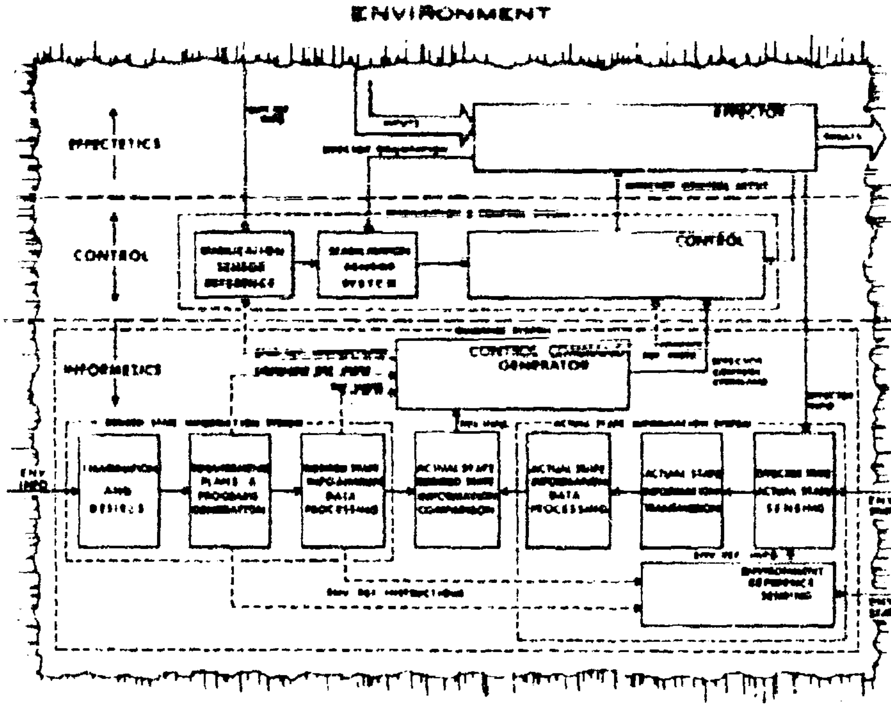


Fig. 8. Generalized functional diagram for an operating system.

geometrical references for the control system. The second control system function is to transform deviations between actual effector situations and selected reference conditions into effector control system inputs for correction of these deviations. A third control system function is to change the stabilization references in accordance with control command inputs. As suggested by the small sketches placed in the control systems component "boxes" of Fig. 5, the pilot's senses, his nerves, his brain, and his muscles provide all the control system functions. His eyes see the earth's horizon and its landmarks as the geometrical references for sensing deviations in stabilization. His body, arms, and hand act to couple control system outputs into the elevator, wing warping, and rudder systems of the aircraft. His nerves transmit stabilization and control command information to his brain where it is processed, and proper corrective signals are sent to his muscles which couple his control outputs to the effector.

It is a fact that the functions of aircraft stabilization and control were not natural capabilities of human beings in the days of the Wright brothers. This situation still exists, but, as in the beginning, it is possible with patience and proper education to train normal persons so that they can satisfactorily provide stabilization and control functions under not-too-severe conditions for limited periods of time.

In Fig. 5 the function of generating control command information is shown as being performed by the guidance system. This system includes four sections: 1) The Desired State Information System receives environmental information that stimulates imagination and desires and generates reference information that represents desired states of the effector system; 2) The Actual State Information System senses conditions of the effector and the environment and generates information representing the actual state of the effector; 3) The Actual State-Desired State Comparator receives input information from items 1 and 2 to generate output information on the deviation of the Actual State from the Desired State; and 4) The Command Generating System receives the deviation information of item 3 and generates control command information.

Figure 5 indicates that in the Wright Flyer System all of the operating components in the four systems listed previously have their functions provided by the human senses, nerves, and brain of the same man. Remarkable as this seems, a relatively short schooling in flying has always given normal human beings the ability to conceive and plan trips in the air, to check on the progress of their flights, and to take necessary corrective actions on the basis of observed "off-course" errors. These statements, of course, depend upon the availability of continuous visual contacts with the earth. When these contacts are shut off for any reason, human senses no longer can provide geometrical references. With these gone the flight vehicle system is liable to catastrophic failure. Methods for eliminating difficulties of this kind will be discussed later.

C.

Generalized Functional Diagrams for Operating Systems, Subsystems, and Components

Figures 6 and 7 represent the functional diagrams for various subsystems and components of the over-all generalized functional diagram of Fig. 8. All the diagrams in this series of figures are consistent in concepts, in pattern, in terminology, and in application to the ideas associated with Fig. 5, which obviously represents an application of Fig. 8 to the special case of the Wright Flyer with a human pilot.

It is important to note that all the statements of the preceding discussion apply equally well to functions realized in any possible way, whether these functions are provided by nonliving or by living entities. Thus, the question of *automation*, which is the replacement of human functions by actions of inanimate devices, is not involved in the generalized concepts associated with operating systems. Certain special situations in which combinations of animate and inanimate components or completely inanimate systems appear for various reasons will be considered later as examples.

It is important to notice that, so far as the over-all functioning of an operating system, which is by definition an arrangement serving as a means for the purposeful accomplishment of some desired result, and the functions of subsystems and components are concerned, the human-piloted Wright Flight System must have included all the essential working elements suggested in Fig. 8. The components

making up the airframe effector and the control surface drivers are clearly visible and identifiable. It is otherwise in the region of informetics, where, though it is absolutely certain that all functions required by the operating chain must have been present, the actual means were concealed within the complex living structures of the human pilot and, as such, were beyond observation as individual working components.

Although the complex of chemical elements and molecules which determine consciousness and activities for animate beings has surely accomplished many wonders during its evolutionary climb from the slime of prehistoric seas, it has never in all of history and does not now completely understand its own functioning. It is, however, safe to say that at present imagination and desires can only be associated with human minds. This means that the initiating component in the desired state information system must, in the foreseeable future, always be made up of men or be directly dominated by men. Out of imagination, desires, and needs come requirements, plans, and programs which may be either generated by men or by men assisted by inanimate devices such as computers. Processing of requirements, plans, and programs information may be carried out by human clerks or be accomplished by properly programed computers to produce desired state information in forms suitable as reference data for system operation.

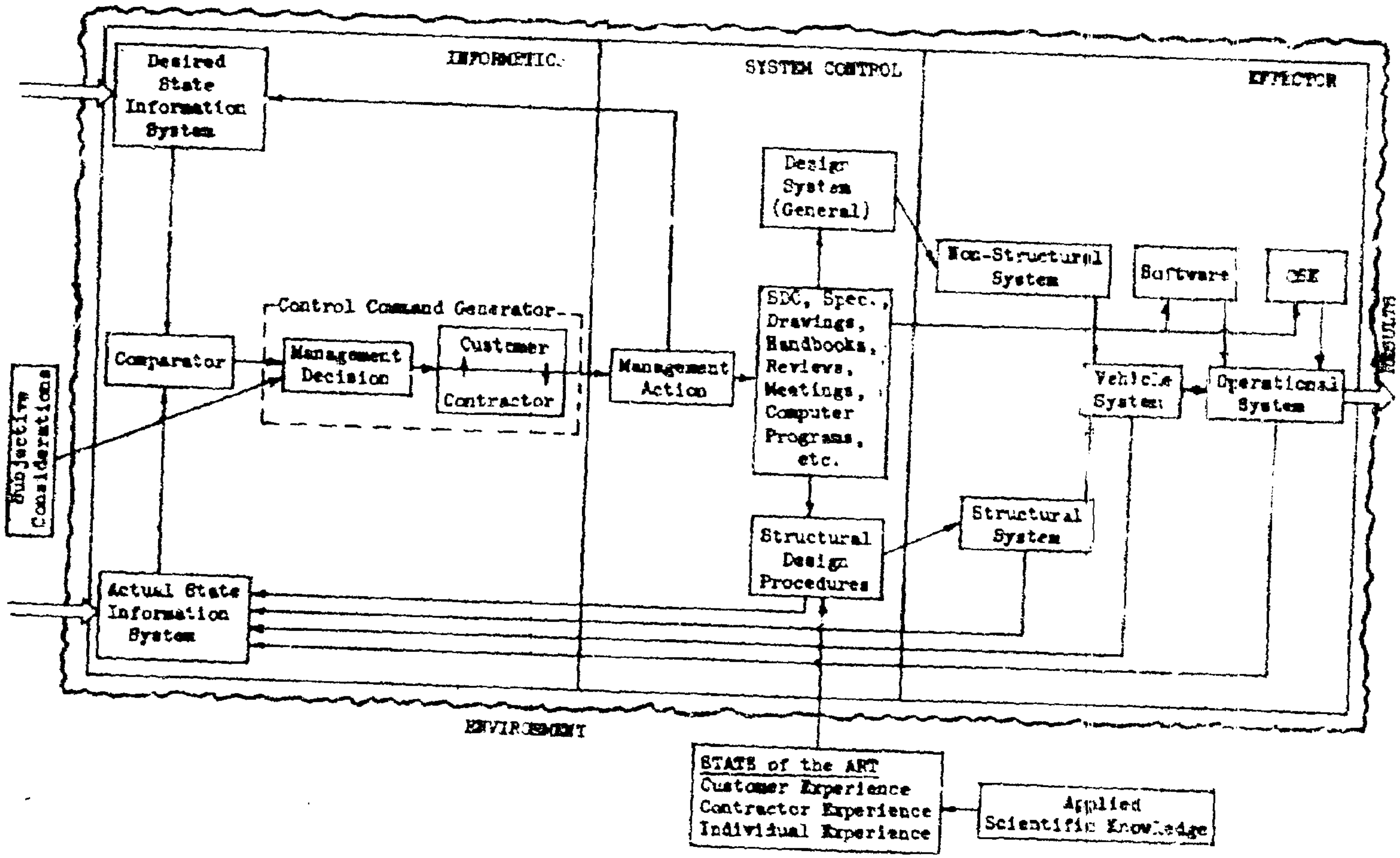
In order to make sure that the effector of any operating system is giving results that match the desired results, it is necessary to determine the results actually being achieved in terms that may be directly compared with corresponding data that represent desired results. For this purpose, the generalized diagram of Fig. 8 shows an Actual State Information System that senses information from the environment and the effector with respect to references established by instructions from the Desired State Information System. The Actual State Sensing System generally produces signals in accordance with plans and programs which may first come into existence at distances of considerable magnitude from other system components. For this reason, provision must be made for transmission of sensed information over distances that may range from zero to millions of miles. With communication technology now well developed and signals almost universally electrical in form, information transmission may be expensive, but is generally possible. With sensed data signals available at any desired location, the next step is to process these signals so they are reduced to forms that are directly compatible with desired state information. In simple situations this processing may be done in a man's head or in more difficult circumstances it may be carried out by complex electronic computers. The means used is not the essential matter, rather it is the fact that Actual State Data have been reduced to terms in which it can be compared directly with Desired State Data.

The Comparator, which carries out this process, gives deviation information as its output. With this information available, the next step is to generate proper Correction Command Information to be supplied as an essential input to the Command Generator. This component, under reference instructions from the Desired State Information System, produces the Command Information which is the basic input for the Control System to determine changes in the stabilization reference conditions

All of the individual functions that have been discussed, and the integrated complex of functions that make up the Guidance System of Fig. 8 which generates commands for the Control System, were supplied by a single man in the Wright Flyer. Since 1903, guidance has seen so many changes that only a thick book written after much research could describe all of them. There is no thought that this paper can do more than highlight some of the major steps on the way to present-day technology, and perhaps to suggest something of the paths that will probably be followed in the future. With this objective in view, a few cases from aeronautics, missile flight, and astronautics will be cited as illustrative examples.

2.3 STRUCTURAL APPLICATIONS

As noted in the introduction, Draper's concept is universal. Therefore, the logic represented by Figure 8 is directly applicable to the structural system. Figure 9 shows the structural version using structurally-oriented terms with the various portions of the system retaining the same functions as in Figure 8. It is most interesting and informative to note how various practices and procedures that have resulted in successful structural systems in the past are explainable in terms of the informetics concepts. Likewise, the new approaches advocated in various papers such as References 3 through 15 and others can be evaluated in terms of this system. This type of discussion will be developed later in the report. Before going into such detailed discussion, it appears desirable to describe the functions in Figure 9 in general terms.



GENERALIZED FUNCTIONAL DIAGRAM — STRUCTURAL DESIGN SYSTEM

FIGURE 9

The development of a structural system and its integration with non-structural systems into the vehicle system and thence into the total operational system involves a series of management decisions. Management actions follow to implement the decisions. Information on the results of the actions may be available in varying amounts. This information, when fed back to the management, may be the basis for making a new decision and repeating the cycle. Each decision is based essentially on whether or not the system as it exists at the moment or as it is expected to be in the future, meets some formally specified or intuitively understood requirement. If the decision is yes, the design, test, fabrication and operation of the vehicle proceeds. If the answer is no, a decision is made on what sub-system(s) to change.

In Draper's terminology, there is a Desired State Information System that provides a definition of the Desired State. There is an Actual State Information System that provides feedback on the Actual State resulting from the various decisions. Finally, there is the Comparator that reveals the status of Actual State vis-a-vis the Desired State. This forms the basis for the Management Decision. As Draper says, "In order to make cure that the effector of any operating system is giving results that match the desired results, it is necessary to determine the results *actually* being achieved in terms that may be *directly* compared with corresponding data that represent desired results." In order to compare actual with desired results the data must be essentially numerical and, thus, objective. It is recognized that some decisions are made without the benefit of (or even in spite of) the appropriate data. This path is recognized by introducing subjective considerations from the environment. Remember that environment is the total complex of all the things with which interactions may occur. By Draper's definition, any factor not singled out for special attention remains with the environment.

It is usually accepted that it is preferable to be objective insofar as possible. Decisions made on a quantitative basis are consistent and repeatable. Different people will make the same decision, given the same numbers. Many decisions, of necessity, are made on a subjective basis and properly so. However, it is a premise of this report that the objective decisions based on quantitative considerations are inherently better decisions.

The system state to which we are referring in the Actual State-Desired State Information System may be one parameter or it may be an infinity of parameters. The region-of-interest is selected. Thus, it is what we say it is. The system state may be represented by a

structural reliability value or by a margin of safety. It may be represented by the probability of exceeding a specified load factor or by the number of Unsatisfactory Reports (U.R.) received from the field.

On the Desired State side of the picture, it should be noted that Figure 8 shows that the starting point is Imagination and Desires. This is so broad that it encompasses everything from a precise calculation to a guess, pure and simple. On the Actual State side of the picture, the most important part of the Actual State Information System (ASIS) is the Effector Actual State Sensor. If the system is going to be quantitative, something must determine the value of the parameter that represents the state under consideration. If the actual parameter is measurable, the data processing system converts the measured quantity into the form needed for comparison. It is obvious that there can be no comparison of Actual and Desired States unless there is a sensor for the Actual State. Furthermore, a measurement of the Actual State is not unique. As in any sensing and measuring procedure, the accuracy of the measurement is of paramount importance in the significance of the quantity derived from the measurement.

The reader is more likely to grasp the true meaning of Draper's terms applied to structural problems if the present structural design system, which is well known to all aerospace structures engineers, is outlined as an informetics problem in considerable detail. Further understanding can be gained by following the procedure corresponding to what would be done if the frequently proposed system of specifying quantitative structural reliability requirements should be adopted in the future. The following sections will discuss these two systems as informetics problems.

2.4 PRESENT (FACTOR OF SAFETY) STRUCTURAL DESIGN SYSTEM

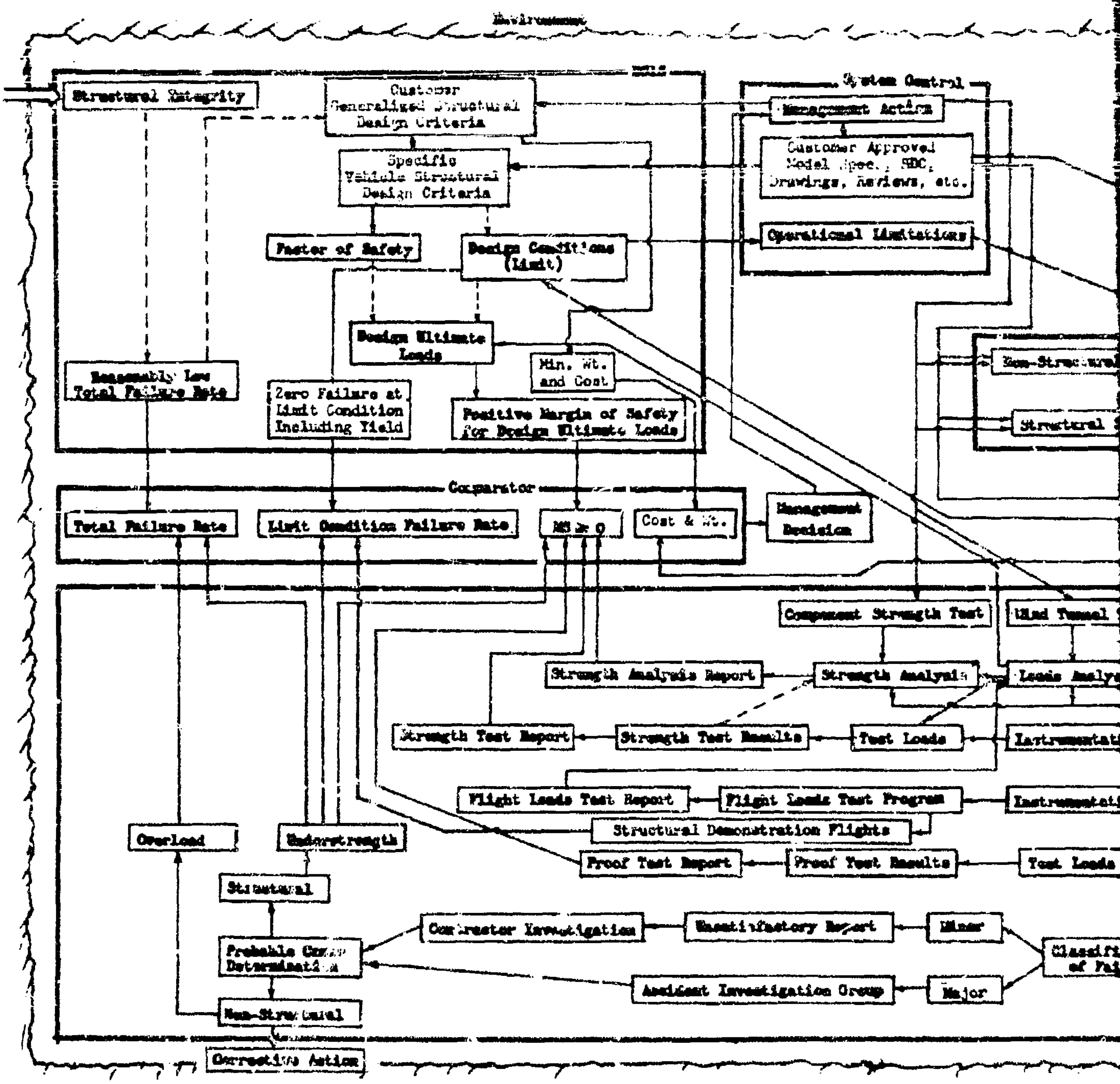
The present structural design system and associated procedures can be outlined and explained very lucidly in Draper's terms. Rather than develop the discussion of the individual subsystems before presenting the whole system as Draper does in Figures 6, 7, and 8, it appears desirable in proceeding through the analysis of the structural design system to reverse the procedure. There are so many iterations in structural design that it will help to keep the function of each step in perspective, if its relationship to other steps is always visible. Accordingly, Figure 10 is presented as a generalized functional diagram showing how the present structural design system operates.

It has not been clearly understood in the past that the major function of the structural design system is to make decisions. Structurally, these decisions are principally concerned with the question of whether or not the structural system is "strong enough" to satisfy the requirements of the vehicle system. Obviously, it is necessary to know what the requirements are before anyone can tell whether the requirements are being met. This is the Desired State side of the system.

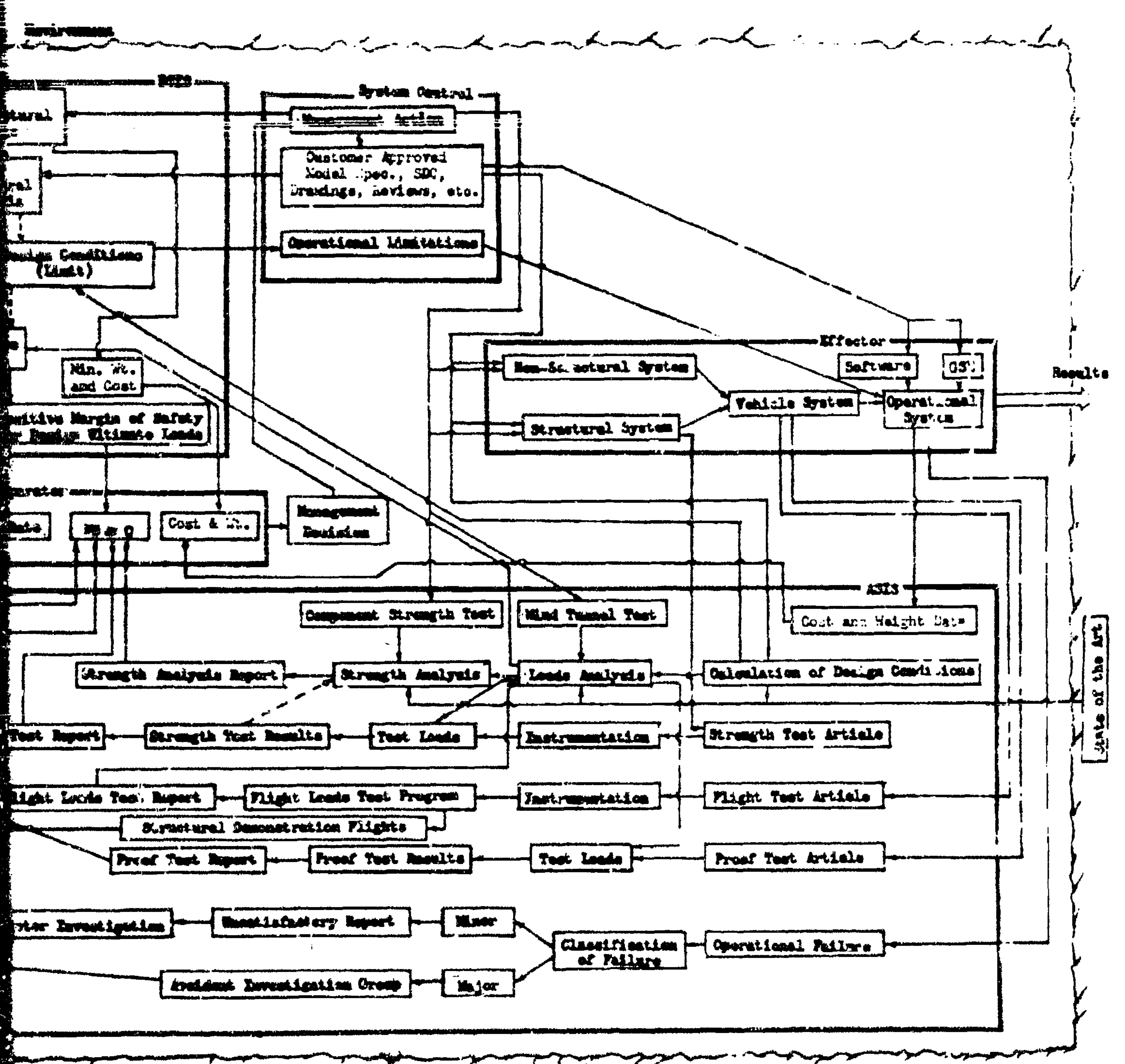
In order to make the decision, some form of definition of the actual state of the structural system must be available. Generally, this definition is numerical but, unquestionably, many decisions are made on an intuitive basis. Even these are likely to be the result of the decision-maker's subconscious estimation and evaluation of many parameters. This process is concerned with the Actual State side of the system.

As Draper points out, the definition of the Desired State and Actual State is really part of a system of collecting and applying information. Then, as shown in Figures 8, 9, and 10, the information is compared, decisions are made, and actions carried out. There may be many iterations of a particular loop to arrive at the desired state of a particular parameter. There are many points where there is feedback of information from one loop to another loop. One of the benefits of the type of analysis conducted in this report is that it makes one organize his thoughts and develop his understanding of why various procedures are followed and the interrelationship between the various steps.

Quantitative data from the Actual State and the Desired State Information Systems are fed into a Comparator. The results of the comparison become the basis for the management decision to change the current form of the structural system or to make no change. It should be noted that management decision in the context of this discussion does not refer to any single individual or organization. The management making a particular decision varies from time to time, depending on the question to be decided. Sometimes the management involved is in the contractor's organization; sometimes in the customer's. Sometimes the decision is made by an analyst signing-off a drawing; sometimes the decision is made at the highest executive levels. The source of the management decision will be discussed at greater length during the detailed discussions. However made, the management decisions are implemented by management actions affecting the various stages in the design and operation of the vehicle system.



Present (Factor of Safety)
Structural Design System
Figure 10



Present (Factor of Safety)
Structural Design System
Figure 10

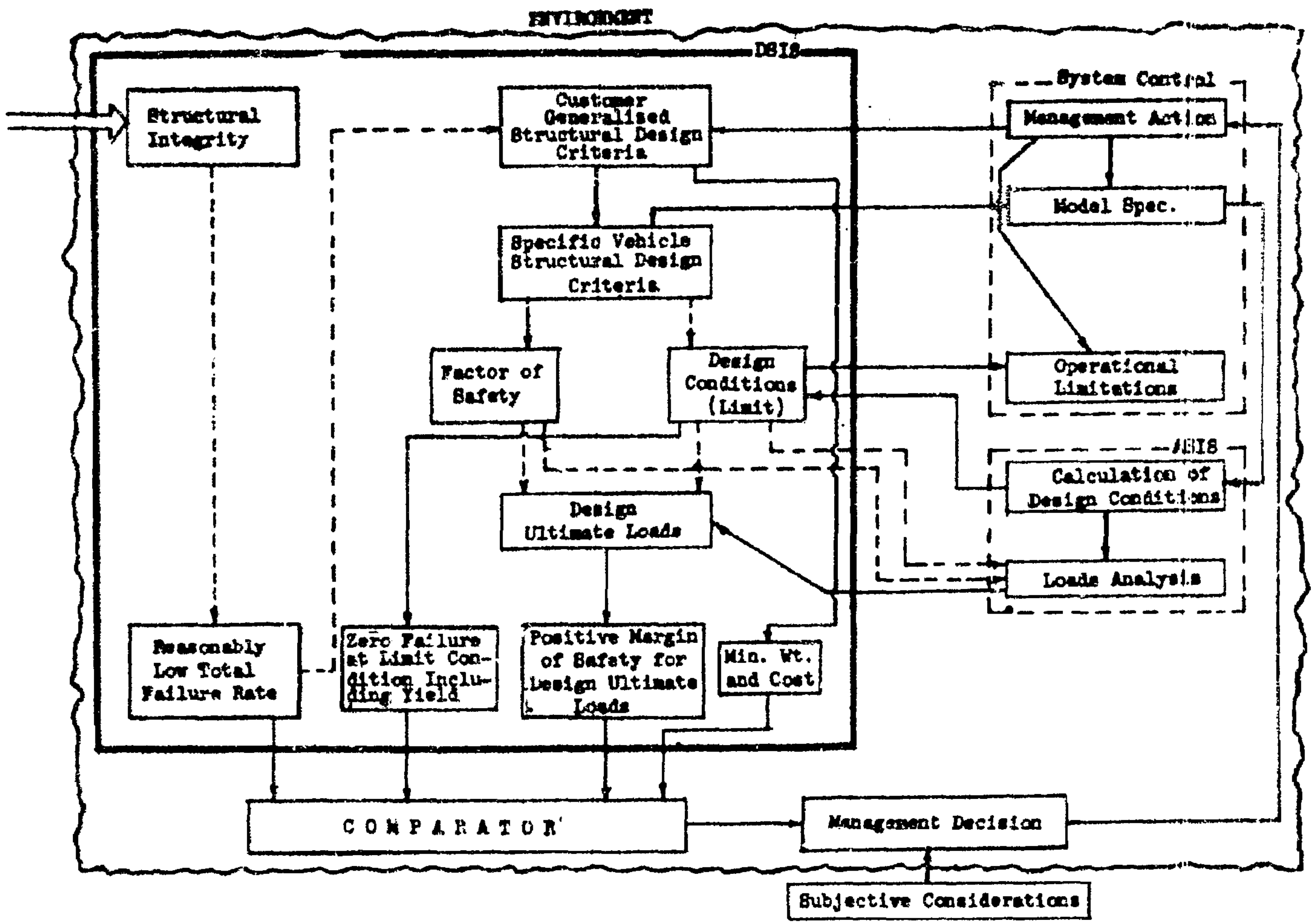
B

a. Desired State Information System (DSIS)

The process of defining the requirements for the structural system involves the Desired State Information System. This system is shown as part of Figure 10 and separately in Figure 11. The Desired State of the structural system originates in the concept that the operational system should have a characteristic vaguely characterized as structural integrity. The term structural integrity means different things to different people. There has never been a quantitative definition established that would satisfy all concerned. There are some who say that the goal is no structural failures. They will not admit that anything less than perfection is acceptable. In this case, actions speak louder than words. If no failures were the goal, the factor of safety would be increased to 2.0 or 5.0 or 10.0. Such an action would certainly bring the failure rates of aerospace structural systems closer to zero than they now are.

Therefore, it is postulated that a "no failure" Desired State is not the true reflection of what has been acceptable in the past. It is generally accepted that the structural system is not required to survive in the face of all possible errors in fabrication, maintenance and operation of the system. A more tenable position is that the structural systems of the past have been expected to have a reasonably low failure rate. However, a precise definition of what is meant by "reasonably low" has not been spelled out. In effect, the definition was reviewed and reestablished on an ad hoc basis every time a failure occurred. Whenever a failure occurred, someone decided the "cause." Then, if the cause was structural, a decision was made either explicitly or implicitly on whether this failure (possibly in conjunction with others of a similar nature) represented "too many" failures. If it did, this became the basis for revising the structural design criteria. As shown on Figures 10 and 11, a management decision of this type, converted into the management action of issuing a new version of the criteria, is the sole basis for the generalized structural design criteria (SDC). In this discussion, generalized structural design criteria means a specification issued by some agency, usually governmental, such as MIL-A-8860 and FAR 25. There is no corresponding document for space vehicles at the present time.

A vehicle structural design criteria document is produced, based on the generalized SDC. This SDC defines the requirements for the particular vehicle system. Certain specific quantities, such as load factors, velocities, trajectories, etc., may be specified in the model specification. Sometimes the model specification will override the generalized SDC and explicitly formulate new requirements.



DESIRED STATE INFORMATION SYSTEM

FIGURE 11

From the vehicle SDC, the limit design conditions are generated. It is an important consideration that these limit design conditions are not generated explicitly as part of a definition of the Desired State. The limit conditions are calculated as a step in the strength analysis procedure which is part of the ASIS (to be described later). Thus, any error in commission or omission in the ASIS analysis will be fed into the DSIS. In such cases, the structural system may have the desired positive M.S., but for the wrong conditions, so the vehicle will fail in operation.

In the design analysis, limit loads are calculated for the limit conditions. Those loads are multiplied by the specified factor of safety to obtain ultimate loads. This operation also is performed as part of the ASIS, but the results are used to define the Desired State. As was the case for the limit design conditions, the design ultimate loads are subject to error which means the definition of the Desired State loads is in error by exactly the same amount as the Actual State loads. Again a positive margin may be shown but the failure rate will be far too high.

The last step in the procedure is that the Desired State is quantitized as a state of the structural system where there is a positive margin of safety (M.S.) for all design ultimate loads.

Summarizing what was described above and shown on Figure 11, the Desired State Information System produces four separate numbers quantitizing the Desired State of the structural system. The first is that there be a reasonably low total failure rate. This number is not really defined but each failure is reviewed and the decision made whether or not to change the structural design criteria. This is an indirect manifestation of whether the failure rate is "too high" without the necessity of defining the discrete number where it becomes "too high."

The second Desired State quantity is a zero failure rate at limit condition or less. This is certainly a definable quantity. The occurrence of such a failure is almost automatically taken as an indication that there is a gross error somewhere in the design or fabrication of the structural system. There should be no failure at limit conditions or less since, by definition, limit conditions are permissible or safe.

The third Desired State quantity is the one that controls most of the structural design. This quantity is the margin of safety. If the calculated margin of safety is negative, the design is modified until a positive margin is shown. If the test strength is lower than the analytical strength, the analysis is usually changed to conform to

the test results and if the M.S. becomes negative the design is modified. If a flight loads program reveals that the loads are higher than predicted resulting in a negative margin, the situation is remedied either by restricting operations or redesigning the structure.

Almost all the structural decisions made during the early phases of the vehicle design are made on the basis of the magnitude of the margin of safety. The other three quantities only become meaningful after production vehicles have gone into operation. Thus, the consequences of any changes required after operations begin are much more drastic than when they result from a negative MS determined during design analysis or during testing. As Coutinho[16] points out, "The earlier in the design cycle that the information becomes available, the more useful it will be."

The fourth Desired State quantity is a minimum cost in terms of either weight or dollars. If weight were not a consideration in the F.S., the desired values for the other three quantities would be much larger. The same is true for the dollar cost. Although there is no procedure for making trade-offs between cost and failure rate in establishing structural design criteria, a reasonable balance is attained by the necessity to be "practical" when considering changes to the criteria. Cost and weight considerations are beyond the scope of the present study and are not considered further.

b. Actual State Information System (ASIS)

The function of the Actual State Information System is to determine as accurately as possible the actual magnitude of the parameters for which a desired value was established in the Desired State Information System. In the analogy of the flight systems described by Draper, the process starts with a sensor that measures some parameter. It is a well-known engineering fact that some instruments are more accurate than others. The sensors in the structural design system have not always been recognised as performing a sensing function. With a little thought the sensor can be identified in each specific situation. Sometimes the sensor is a mathematical calculation, sometimes it is the act of a structure failing or surviving. If no sensor can be identified, it is a strong indication that the procedures being followed are not very purposeful. After all, the function of any operating system is to serve "as a means for the <u>purposeful</u> accomplishment of some desired result."[2]

In the ASIS outlined on Figure 10, there are five different sections and there may be others. Each section corresponds to a different stage in the design and operation of the particular vehicle system. Continuing the analogy to Draper's flight control systems, each section of the ASIS on Figure 10 corresponds to a measurement with a different type of instrument which is progressively more accurate. Each of the five sections will be described separately in the order that they would normally occur in the structural design process.

(1) Analytical Design Stage

The first prediction of the actual state of the M.S. of the structural system results from the analyses conducted during the design stage of the vehicle system. The M.S. calculation is the end result of the strength analysis. It should be noted that this calculation was deliberately labeled a <u>prediction</u>. A prediction and a determination are not the same thing, although Coutinho points out in Reference 16 that, "In the eyes of the analyst, 'to predict' generally means 'to determine.'"

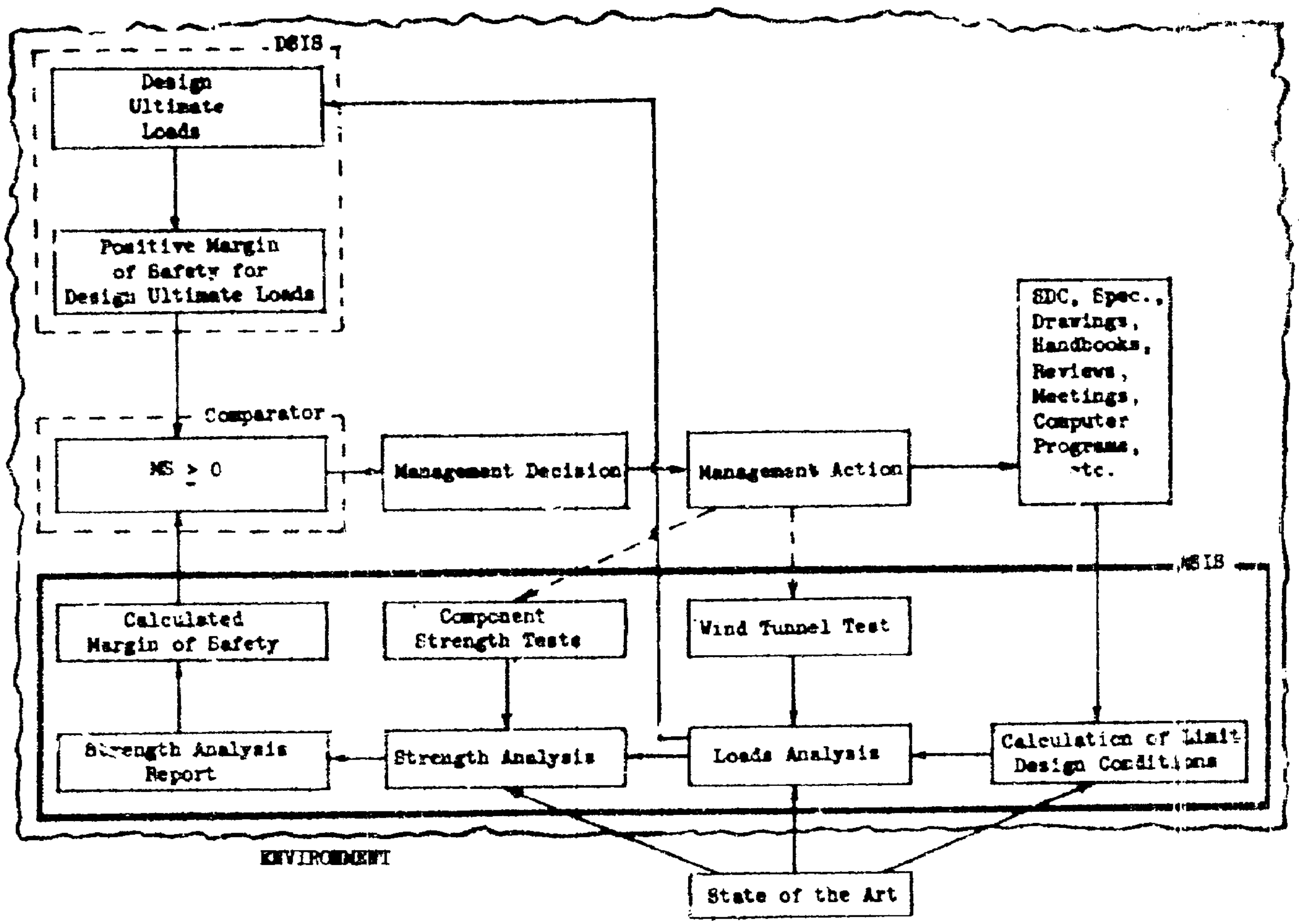
The analysis begins, as shown in Figure 12, with the calculation of limit design conditions. These limit conditions are based on the requirements set forth in the vehicle structural design criteria. A loads analysis follows to obtain loads at various locations on the vehicle for each of the limit design conditions. Wind tunnel tests may be conducted to assist in the analysis. However, wind tunnel tests are not considered a substitute for full-scale flight tests in the verification of the design loads.

The strength analysis follows next using the loads for the specified operational conditions. Component strength tests may aid the analysis at this point. From the strength analysis comes a prediction of whether the structure, as defined by the current drawings and specifications, will support the design loads. The strength analysis report results in a summary of the calculated margin of safety for various critical elements of the structure.

This calculated M.S. is the "indicator" of the Actual State. It is the quantitative parameter that is compared to the desired value. If the M.S. is zero or greater, the design complies with the specification requirements. Obviously, the contractor's management can decide that some more conservative value is required for other purposes. If the M.S. is negative, the decision presumably is to change the design to increase the strength or to change the operation to decrease the load. This results in modified drawings and the process is repeated.

The procedure is presented as though it is a simple, direct process; but any experienced structural engineer knows that the process is anything but simple and direct. Starting with the preliminary design of the vehicle, there are many iterations of the analyses outlined on Figure 12. Often the loads or strength analyses are changed before the strength analysis is completed, so there are many partial iterations. The number of iterations and when they occur does not affect the basic functional purpose of each segment of the Actual State Information System shown on Figure 12.

The only difficulty in using this Analytical Design Stage of the ASIS is that it is somewhat less accurate than needed to assure the low failure rates and high structural integrity usually established by the DSIS of Figure 11. This is analogous to an instrument that measures velocity but does it somewhat crudely. A number can be read from the



ACTUAL STATE INFORMATION SYSTEM
(ANALYTICAL DESIGN STAGE)

FIGURE 12

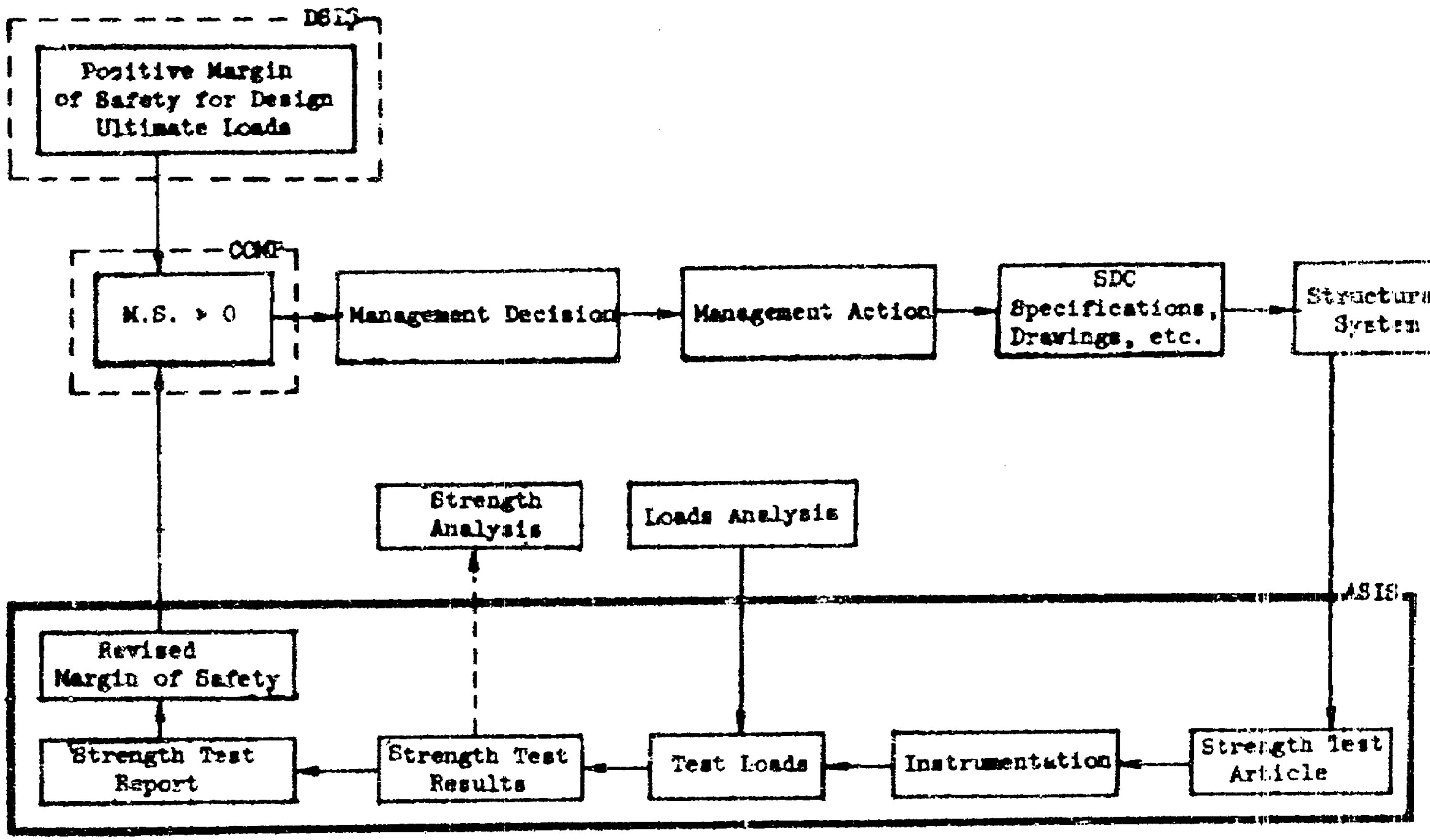
instrument at any time but a large plus and minus value must be attached to the reading to make it meaningful. Reference 17 documents the fact that 13 percent of the aircraft wings tested for the Air Force during the 1940 decade failed at less than two-thirds of the intended value. One percent failed at less than one-third of the intended value. Also, there are many known instances of errors in the loads analysis. There is no indication that the situation has improved for the present generation of aircraft and space vehicles. It is generally accepted that testing is a necessary part of the structural design system. The testing segments of the ASIS will be described in the following sections.

(2) Strength Test Stage

The complete functional diagram presented in Figure 10 shows three branches of the ASIS that involve testing to furnish information improving the prediction of the M.S. The first of these is the Strength Test Stage shown in Figure 13. The previous section noted that the Analytical Design Stage was an imperfect tool for measuring M.S. The strength test typically involves a static test but certainly does not exclude dynamic and fatigue tests. This improves the situation by disclosing, through premature failure during the test, errors in the strength analysis. The beauty of the procedure is that even one test can disclose that it is <u>likely</u> that there is an error in the design causing the premature failure. The failure does not <u>prove</u> that there is an error. After all, it is conceivable that a structural strength, corresponding to a value so low it would occur only once in a thousand or once in a million structures, might have been present in the particular structure fabricated for the test. This could occur with the mean strength and 99-percent exceed strength exactly where they were predicted to be. However, a <u>decision</u> can always be made that any structure failing below the design load is deficient. On rare occasions, the decision will be wrong and a structural system that is already reliable enough will be unnecessarily redesigned for greater strength. On the other hand, it might take hundreds or even millions of tests to <u>prove</u> statistically that the reliability is as high as desired. (See discussion on pages 101 and 109).

The Strength Test Stage of the ASIS begins with the selection of a static test article. It is presumably a representative specimen of the structural system defined by the same drawings and specifications used in the loads and stress analyses. The necessary instrumentation is added. The test loads are essentially as derived in the loads analysis. The results of the static test such as the stresses and deflection associated with particular loads, together with the fact of yield or rupture, feed back to the strength analysis. If there are any serious discrepancies between the analysis and the experimental data, the analysis usually is revised and another iteration of the Analytical Design Stage follows.

The basic instrument that functions as the "indicator" in the Strength Test Stage ASIS is the strength test report. Effectively, the report establishes a new M.S. Obviously, if the structure failed prematurely, the M.S. is negative. A management decision must follow on what action should be followed to eliminate the negative M.S.



ACTUAL STATE INFORMATION SYSTEM
(STRENGTH TEST STAGE)

FIGURE 13

(3) Flight Test Stage

The second of the three test branches of the ASIS is the Flight Test Stage, shown in Figure 14. This performs the function of disclosing error in the loads analysis as the static test does for the strength analysis. The Flight Test Stage of the ASIS begins with the selection of a flight test article. It is presumably a representative specimen of the vehicle including the structural system and all other systems that affect the structural system. Instrumentation is added to measure the loads at selected locations on the vehicle. During the program, loads are measured for various flight conditions, providing information for correlation with the loads analysis. If the loads are different than predicted in the loads analysis, this results in revision of the loads analysis, the strength analysis and then the M.S. If the revision results in a negative M.S., design modification and additional static testing may be necessary and the cycle is repeated.

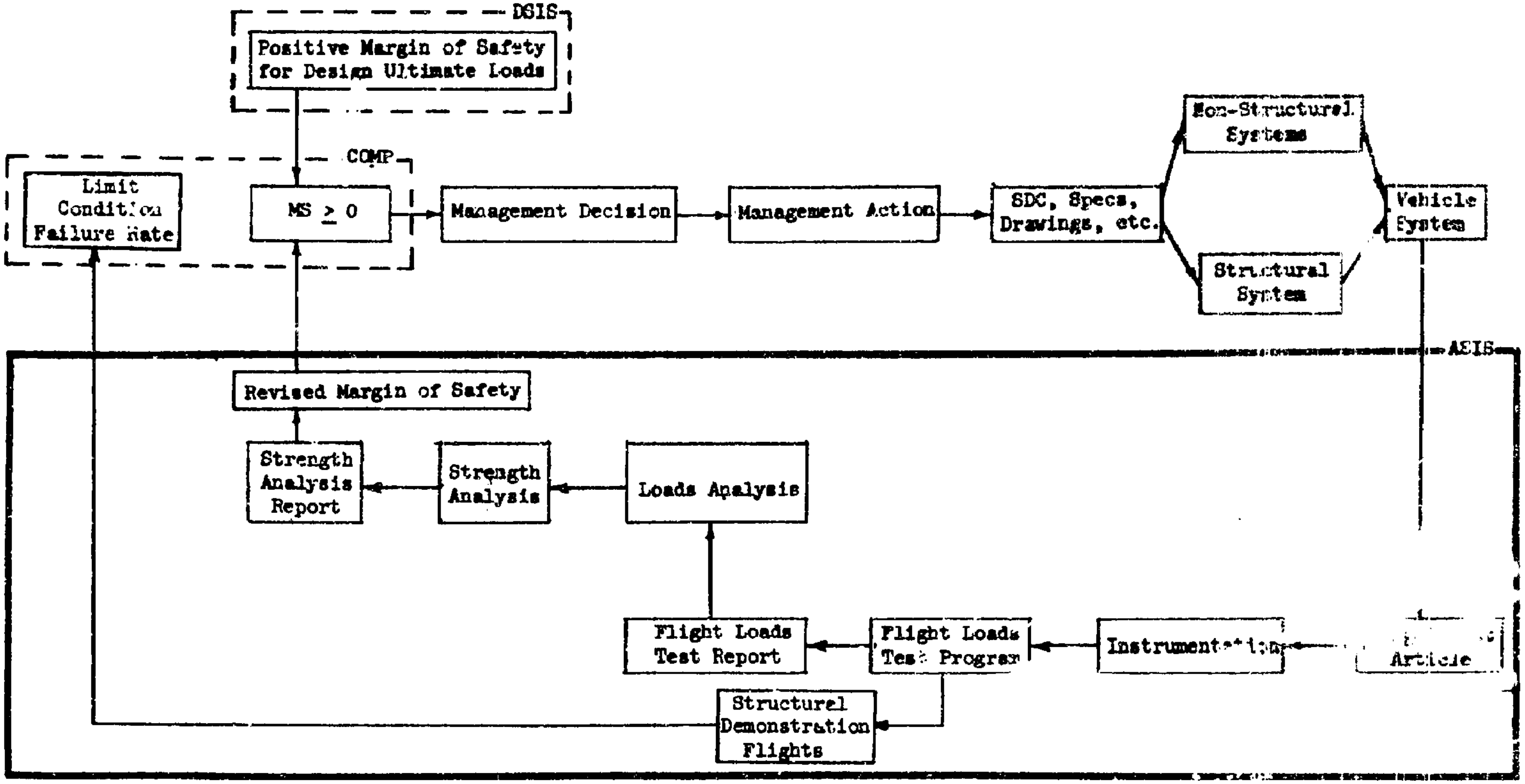
Many Flight Test Stages include Structural Demonstration Flights as indicated on Figure 14. If the structural demonstration is conducted on the same vehicle as the flight loads measurements, the demonstration will represent the extreme condition at which loads are obtained. In addition, the demonstration integrates all of the strength and load considerations into a single proof that the vehicle can actually survive the limit conditions. It occasionally discloses that the strength test did not truly simulate the flight condition.

Generally, the successfuly conclusion of the flight loads test program and the structural demonstration flights signals the completion of the design qualification of the structural system. In aircraft, the interim restrictions are removed and the user is free to operate the vehicle to the limits specified in the vehicle structural design criteria. In space vehicles, where testing and operations tend to coincide, the vehicle system is cleared for extended operations including manned flights.

(4) Proof Test Stage

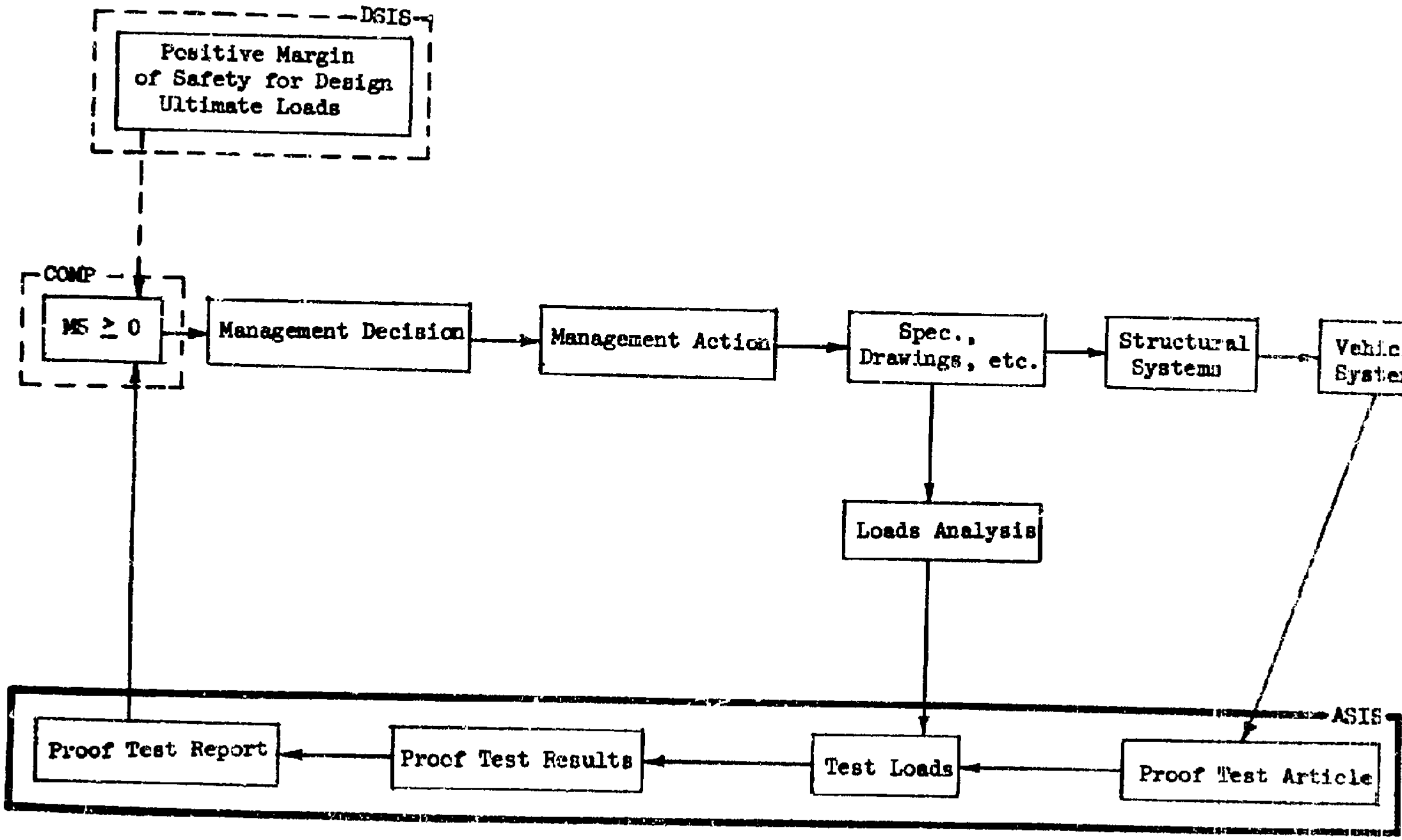
The third and last of the testing stages of the ASIS is the proof test shown in Figure 15. This stage is not an integral part of every vehicle system. However, it has been found desirable or necessary to conduct proof tests on many vehicles before accepting the individual vehicle for service. There are many reasons for such a situation, but they all are based on a single fundamental problem. If there is a significant possibility that the individual structure will be grossly understrength relative to the intended strength even though the average strength is satisfactory, a proof (or acceptance) test may be the answer. Typical situations where proof testing is a desirable and necessary tool occur with welded pressure vessels, some types of bonded structures, and primary control surfaces of aircraft.

Proof testing is comparable to the process described under the Strength Test Stage. The basic difference is that each and every vehicle is subjected to the test rather than one typical system and the number of conditions tested is usually much reduced. Usually,



ACTUAL STATE INFORMATION SYSTEM
(FLIGHT TEST STAGE)

FIGURE 14



ACTUAL STATE INFORMATION SYSTEM
(PROOF TEST STAGE)

FIGURE 15

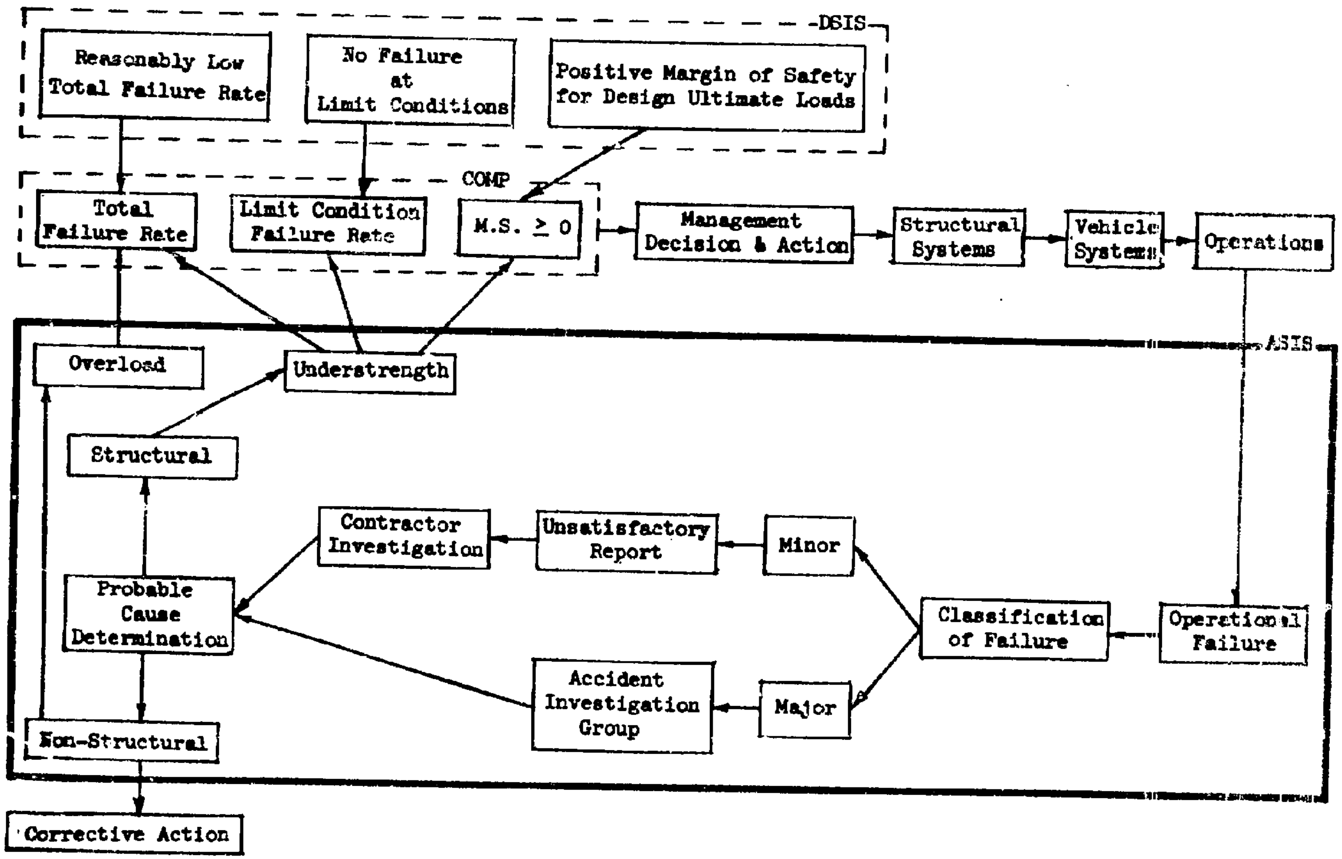
one proof test is conducted to a load somewhat over limit but considerably under ultimate. A more philosophic distinction is that the proof test is concerned with the M.S. of the individual article whereas the static test is concerned with the M.S. of the system comprising many articles. The failure during proof test automatically eliminates the understrength article so no management action is really necessary. However, as shown on Figure 15, the formal resultant of the test failure is the disclosure that the M.S. for that particular article was less than zero.

(5) Operational Failure Stage

The previous segments of the ASIS have been concerned with "measuring" the M.S. before the vehicle becomes operational. The Operational Failure Stage of the ASIS, shown on Figure 16, is concerned with the use of information that becomes available during operational usage of the vehicle system. Any failure of any structural component is usually investigated to determine the "cause" of the failure. This investigation is a final source of information on the Actual State of the structural system. It should be noted that this segment of the ASIS is the only one not completely concerned with M.S. It should also be noted that the failure rate, even at the end of the service life of each vehicle in the system, is not directly convertible into a probability of failure or a structural reliability figure. This is the same kind of statement as saying that obtaining 7 out of 10 heads in the toss of a coin does not correspond to a probability of 0.7. The probability of heads remains at 0.5. The rate of occurrence of an event is only an approximation of the probability of occurrence. When the number of events is small, as in the case of structural failures, the correlation between failure rate and probability of failure may be very poor. As a result, the information on structural failures is usually more useful in the determination of cause of failure and corrective action to prevent reoccurrence of the failure than in establishing reliability levels.

Procedures represented by the ASIS shown on Figure 16 are well known but a brief discussion of each of the functional blocks is warranted. As operations proceed, structural failures occasionally happen. When one does occur, it is initially classified as major or minor. Minor failures are typically yield failures that are repairable, cracks that are not catastrophic and similar occurrences. Major failures typically involve rupture of the component resulting in loss of the vehicle and injuries to the crew. However, it is not intended that the definitions above be anything more than a guide to the meaning of major and minor failures as the terms are used in this discussion.

If the failure is minor, an Unsatisfactory Report (or its equivalent) is submitted to the contractor for investigation and corrective action. If the failure is major, an ad-hoc group, composed



ACTUAL STATE INFORMATION SYSTEM
(OPERATIONAL FAILURE STAGE)

FIGURE 16

of contractor and customer representatives is assembled to investigate and determine the cause. One of the determinations of the appropriate investigating group is whether or not the failure was the result of structural causes. If the decision is non-structural, such a decision is equivalent to deciding that the M.S. is positive and that the structure was overloaded. Corrective action is outside the structural area. The number of occurrences may be compared against the vaguely defined Desired State condition of "Reasonably Low Total Failure Rate" shown on Figure 11. It may be decided at any time in the "Management Decision" block that "too many" failures are occurring due to overloading. Further, it may be decided that the situation cannot be controlled by modifying the operational procedures. In this situation it may be decided that the structure must accommodate the more severe environment. In such a case, what was formerly considered to be an overload must now be considered a design condition. The structural design criteria is modified accordingly.

If the decision on the failure cause is that the structure is understrength, the M.S. is necessarily negative. If it failed at limit conditions or less, the structure must be grossly understrength and the responsibility almost necessarily falls in the manufacturing or maintenance areas. Occasionally the understrength is not attributable to a defect in the individual article but to a basic error in the design. This means that the analytical and testing stages of the ASIS (Figures 12 to 14) were not sufficiently accurate disclosers of the design error. Typically the error in testing stemmed from overlooking the condition completely or from a poor simulation of the actual operational conditions during the test. The same reasoning pertains to failures beyond limit conditions but at a condition that represented a negative margin.

c. Other System Functions

The Desired State Information System and Actual State Information System are the key elements in any operational system. The same is true in a structural design system. The DSIS and ASIS furnish the information used in making the decisions but many other functions contribute to the final result. These other functions are described in this section and shown on Figure 10.

The Comparator furnishes the numerical value of the difference between the desired state value of a parameter and the actual state value. In structural design this function is not usually formalized. Typically, the strength analysis report has a section listing the lowest values of the margin of safety. Each listed value of the M.S. is an output of the ASIS to the Comparator. Since the Desired State

is for an M.S. ≥ 0, the output from the Comparator is the same as the input. For this reason, there tends to be some blurring of the difference between the two functions so that it is not readily apparent to all concerned that there are two separate functions.

Occasionally, something breaks down in transmitting the information on M.S. to the proper management. When this happens a deferred discovery of a negative M.S. may occur with its attendant increase in difficulty of correcting the situation. In any design system, the procedure for quantifying the difference between the Desired and Actual States must be clear-cut or the decisions may not be properly objective.

The Management Decision function in the Present System corresponds to the Control Command Generator in Draper's analysis as shown on Figure 8. In the Present Structural Design System, it represents the decisions at many different levels. No attempt is made in this report to outline all the decision making apparatus. It includes both contractor and customer personnel. As an example, a stress analyst in the contractor's organization might decide that a particular design had a negative margin and the designer might concur, making the change immediately. No higher authority might be involved. Eventually, all of the loads and strength analyses must be approved by the top management in the contractor organization. Then, the reports are submitted to the customer organization for approval. Thus, the final management decision involves approval of previous decisions and many iterations of these decisions all along the line.

Management decisions are translated into action that takes many forms. Management action leads to cutting metal in fabricating a test structure. It also leads to revisions in the structural design criteria. Or it may lead to a release of a design for production. All elements in the design, fabrication and operation of a vehicle system are the result of a management action regardless of who actually performs the action. These management actions are equivalent to pulling on the control stick in Figure 5; such things as specifications, drawings and handbooks are part of the System Control. These are the means whereby the management decisions are translated into the desired interaction between the Effector and the environment.

The Effector in the Structural Design System is the hardware corresponding to the structural system. There are many steps, between management action and the hardware, that are not explicitly shown. These include materials producers, manufacturing systems, quality control, and subcontractor relationships. These all contribute to the Actual State of the structural system and must be considered in a complete analysis. Also, any failure in the structure may be traced to one of these subsystems and the management decision may bring about corrective action at the appropriate level.

Non-structural systems are combined with the structural system to achieve a vehicle system. Here again, there are many interfaces with the structural system. For instance, an actuator produces a force that the structural system must withstand. Less obvious are requirements that the structural system must tolerate malfunctions in other systems. In many cases of structural failure of this type, the decision on corrective action may be an arbitrary management decision. It may be decided that the failure in the other system that caused the structural failure must be corrected and the structural system remains unchanged. On the other hand, there have been many decisions that failures in other systems become part of the environment that the structural system must withstand. Such decisions usually result from problems in making the other system reliable enough without excessive cost, weight, or development time.

The vehicle system together with its ground support equipment constitutes the operating system. What might be called software could be included in the operational system. Software might include pilot's handbooks, launch limitations, flight plans, and similar items. These all have interfaces with the structural system and decisions must be made on the division of responsibility between the various systems. Roughly hoisting the capsule of a space vehicle might result in failure at the hoisting lugs. Corrective action could require stronger lugs or the action might be to revamp the hoisting procedure to eliminate any sudden hoisting movements, thus controlling the magnitude of the hoisting loads.

Another example of software is the provision of weather information affecting the vehicle operation. In space vehicle launches, a careful prediction of the winds aloft is made before each launch and ground rules are established to hold a launch when excessive winds are expected. Similar actions are taken in aircraft operation to predict areas of high turbulence and to vector the aircraft around stormy areas whenever possible.

Each of these systems has an interface with the structural system and decisions are needed on where the line of demarcation lies. Obviously, a decision can always be reversed and new requirements imposed on the structural system. There is no hard and fast rule on how to make these decisions. Whatever the decision, it should always be an explicit decision and the decision should be communicated to those responsible for managing the system in question. If this is not done properly (lack of proper communication has been a problem in the past), the opportunities for structural failure will multiply unnecessarily.

2.5 PURELY STATISTICAL STRUCTURAL RELIABILITY SYSTEMS

The introduction of a structural design system, with a purely statistical structural reliability basis, has been proposed by many authors.[3,4,5,9,10,11,12,13,14,15] The concept is very attractive. For one thing, it quantitizes the design requirements in a rational fashion. If the reliability of the structural system can be ascertained, it can be incorporated with the reliabilities of non-structural systems to obtain an overall reliability for the total vehicle system.

This seemingly attractive concept has never been accepted by the aerospace industry for general use in the design of structural systems. An examination of the purely statistical structural reliability procedure from the informatics viewpoint discloses some of the reasons for this lack of acceptance.

a. Desired State Information System

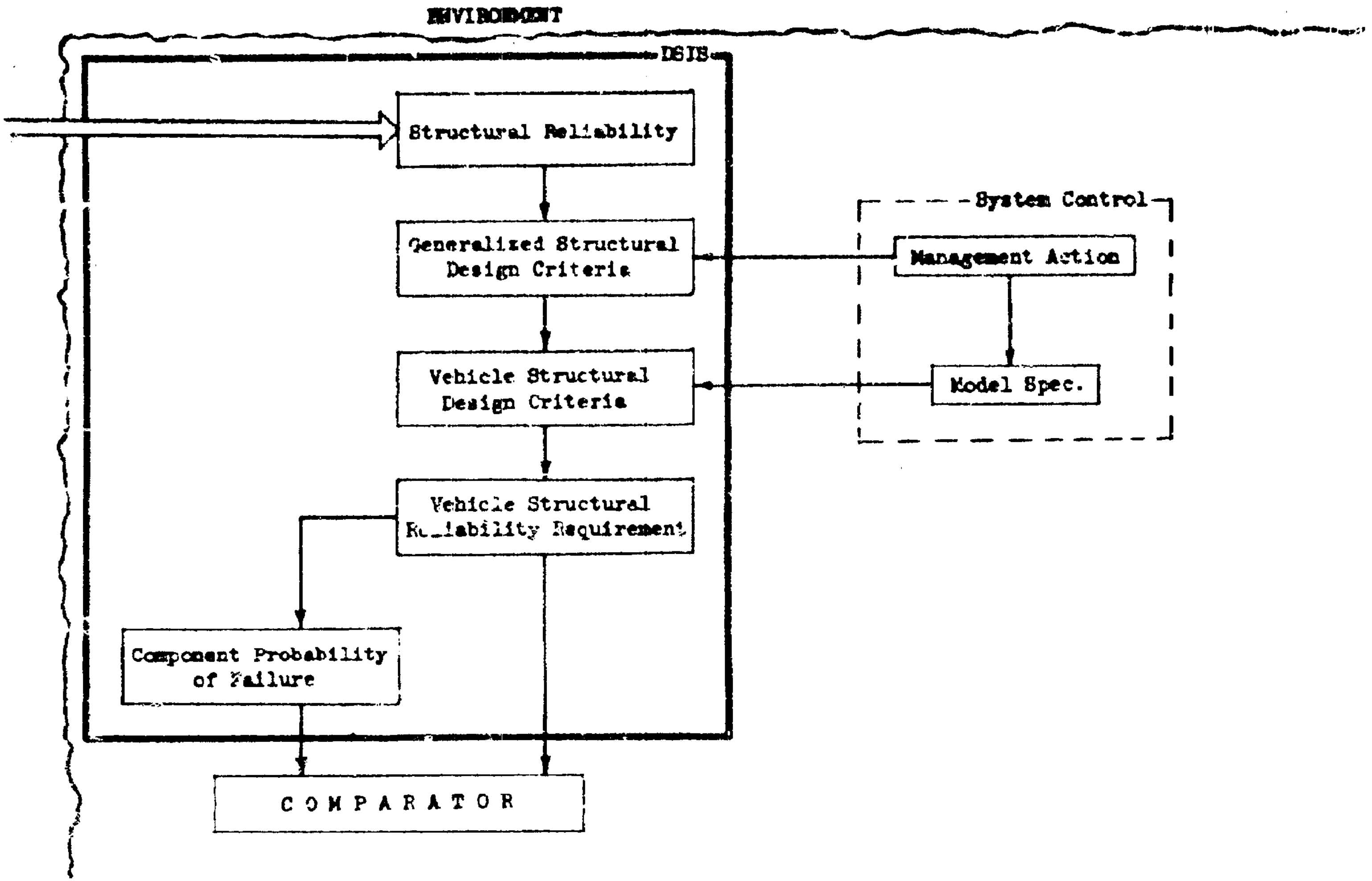
The definition of the Desired State for this type of structural system is simplicity itself. It is shown in Figure 17. Management action can establish a desired structural reliability for various classes of vehicles in the generalized SDC. The model specification can establish a classification appropriate to the mission requirements for that particular model. This quantitizes the structural reliability requirement for the vehicle system in question. As an alternate, the desired reliability for the complete vehicle can be established. The required structural reliability can be allocated to be consistent with the other elements of the vehicle system. Either way a single number, such as 0.99999, can represent the Desired State of the structural system. This number can be further subdivided to allocate a structural reliability or probability of failure to each component in the structural system.

b. Actual State Information System

The Actual State Information System for a structural reliability design system has many of the same functions as the ASIS for the present structural design system. Analyses are accomplished, tests are conducted and the results of operation are collected. Numbers representing the Actual State of the structural system are generated. Individual segments of the ASIS are described in the sections following.

(1) Analytical Design Stage

The functions involved in the Analytical Design Stage of the ASIS of a Purely Statistical Structural Reliability Design System are



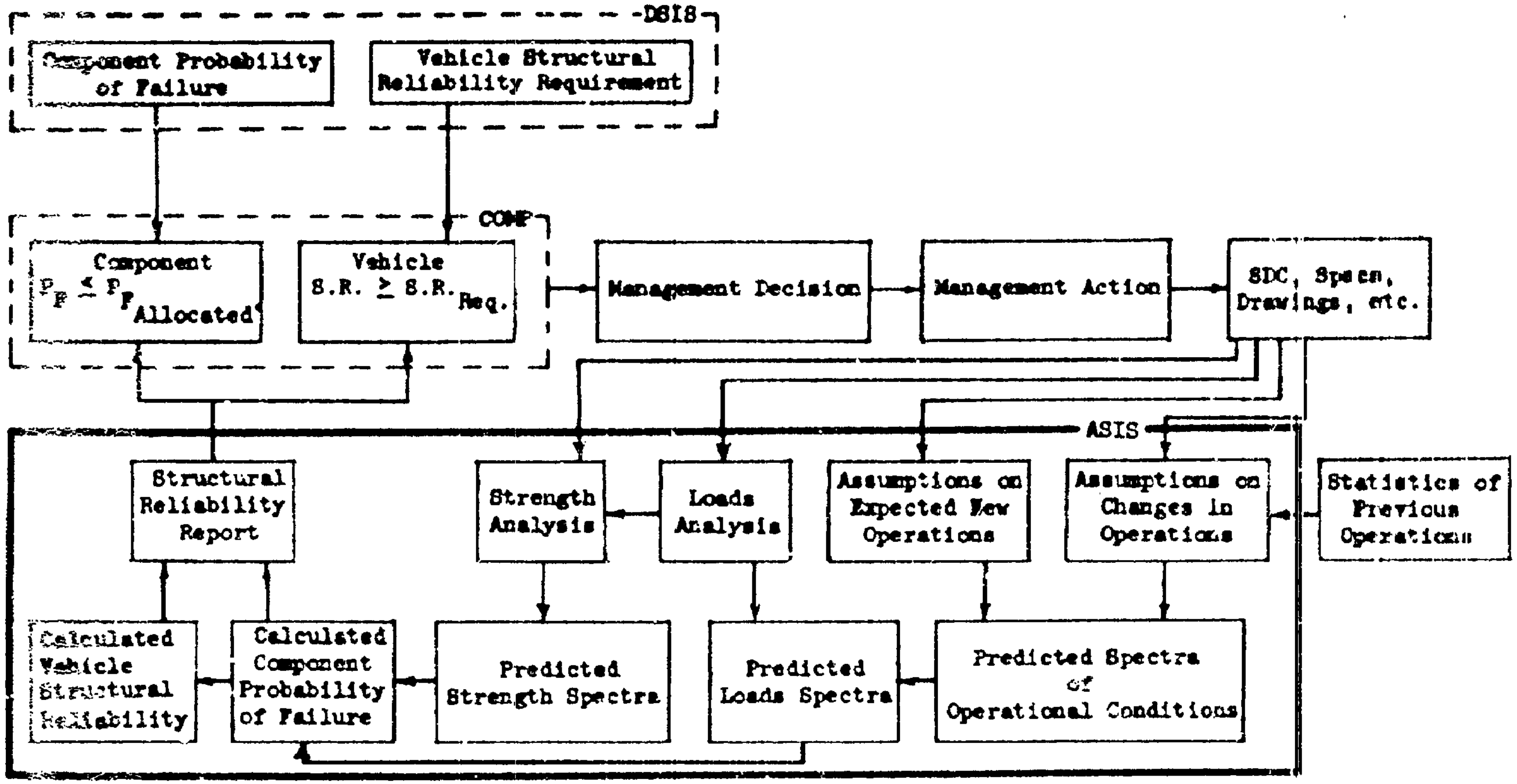
STRUCTURAL RELIABILITY DEIS

FIGURE 17

depicted in Figure 18. Instead of starting with the definition of a limited number of discrete conditions as in the Present (Factor of Safety) Design System, the probability of attaining various operational conditions must be calculated. In general, the statistics of one variable are dependent on the magnitude of other variables. Thus, the calculation of the probability of exceeding a condition defined by several variables is a complex task; but, theoretically, it is possible.

Loads analysis in the Purely Statistical Structural Reliability System is comparable to the same function in the present system. If the load on a particular component is known for a particular operational condition and the probability of attaining that condition is known, the probability of attaining that particular load for the particular operational condition is known. Then, if the probabilities of attaining that load for all other operational conditions are determinable, all the probabilities can be combined to obtain the total probability of obtaining the load. Repetition of the process for all load levels is necessary to obtain the load spectrum for each component. The process must be repeated for each component considered. The distribution of failing strengths of each component can be computed using the same strength analysis procedures used in the present system. Additional statistical data must be introduced in connection with such parameters as dimensional data and failing stress.

The strength and load distributions can be combined to determine the probability of failure of a particular component. Then, the probabilities of failure of each component can be used to calculate the system probability of failure, which is the complement of the system probability of survival. The probability of survival of the system for its operational lifetime is the structural reliability. The calculated values of system structural reliability and the component probabilities of failure can be compared to the desired state values. The management decision on whether the actual structural system will achieve the desired reliability can be made on the basis of this comparison. However, the same problems of accuracy in the loads and strength analyses that occur in the Present System will occur in the Structural Reliability System. In addition, more problems will occur in predicting the various probabilities concerned. Therefore, an analytical calculation of probability of failure and structural reliability cannot be considered to be accurate enough to serve alone as the ASIS in a structural reliability system. References 3 through 8 discuss various aspects of the error problem in determining structural reliability. Experimental or test data are needed more than ever to verify the predicted values. Reference 8 shows that the actual structural reliability drops to approximately 0.9 whether the



PURELY STATISTICAL STRUCTURAL RELIABILITY ASIS
(ANALYTICAL DESIGN STAGE)

FIGURE 18

intended value was 0.99 or 0.999999 when the error frequency documented in Reference 17 is introduced into the calculation. It is suspected that most structural designers have an intuitive understanding of the lack of accuracy in the purely statistical analysis of the problem. This is the basis for their usual rejection of the structural reliability concept.

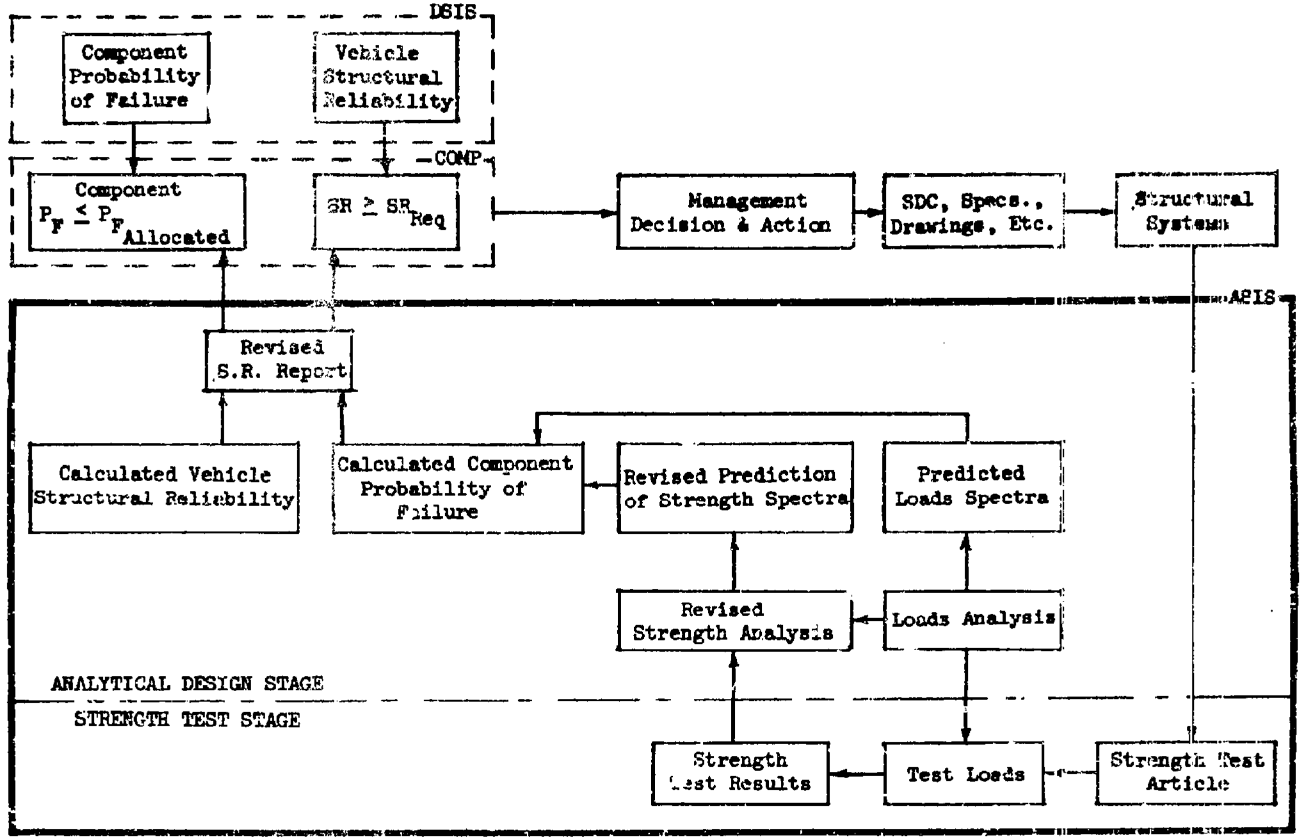
(2) Strength Test Stage

As shown on Figure 19, the Strength Test Stage as presently constituted does not function directly as an ASIS in the structural reliability design system. Meaningful measurements of structural reliability or probability of failure for comparison with the DSIS values simply are not possible with one or two strength tests. Hundreds or possibly millions of tests would be required to define accurately the statistical characteristics of the structural system to a degree compatible with the desired reliability.

As shown on Figure 19 the end result of the test is to correct the strength analysis where errors are disclosed. This correction leads to revised prediction of the strength spectra and of the structural reliability. Unfortunately, these S.R. predictions still incorporate many errors that were present in the original prediction. The contrast between the Strength Test Stage ASIS in the Structural Reliability system and in the present M.S. system is marked. In the Present M.S. system, the Strength Test Stage can stand by itself as a measuring system to furnish information for management decisions. Even if there is no analysis at all, the structural system could be defined on a trial-and-error basis. The Strength Test Stage alone could function to accept or reject the resulting design. Such a situation does not exist in the Purely Statistical Structural Reliability System.

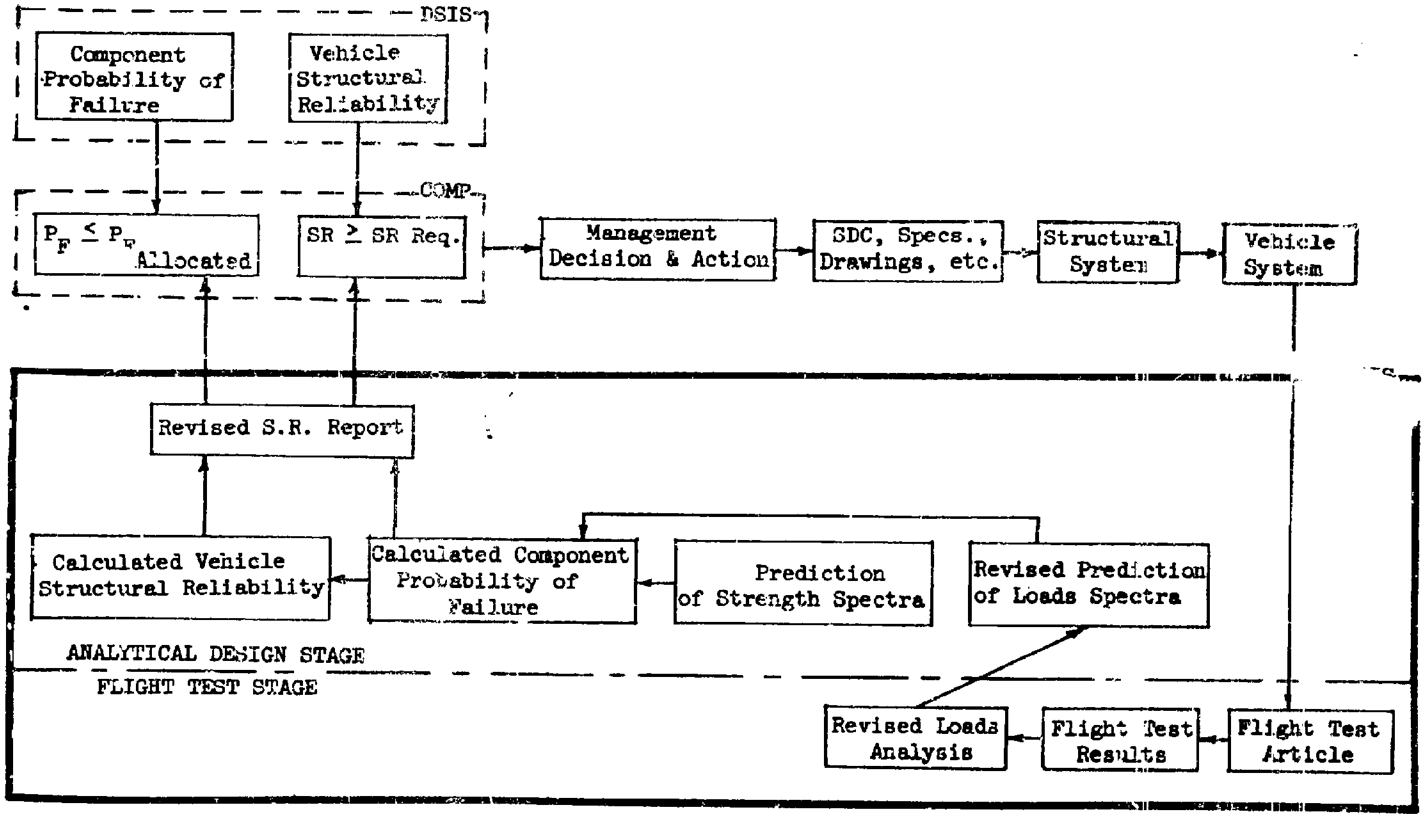
(3) Flight Test Stage

As shown on Figure 20, the Flight Test Stage does not function as an ASIS to the extent it does in the present system. The principal purpose the flight test serves is to revise the loads analysis as necessary. A typical flight test program does not and cannot provide information on the probability of exceeding given flight conditions. Even if the attempt were made to obtain statistical data, the success of the program would be problematical. There is always a question whether the statistics of operations during a test program represent the statistics of operations that will occur under the control of the normal user. Furthermore, the flight test program is usually constrained by cost considerations to represent a very small portion of the total usage, which reduces the possibility of obtaining any meaningful statistical data.



PURELY STATISTICAL STRUCTURAL RELIABILITY ASIS
(STRENGTH TEST STAGE)

FIGURE 19



PURELY STATISTICAL STRUCTURAL RELIABILITY ASIS
(FLIGHT TEST STAGE)

FIGURE 20

(4) Operational Failure Stage

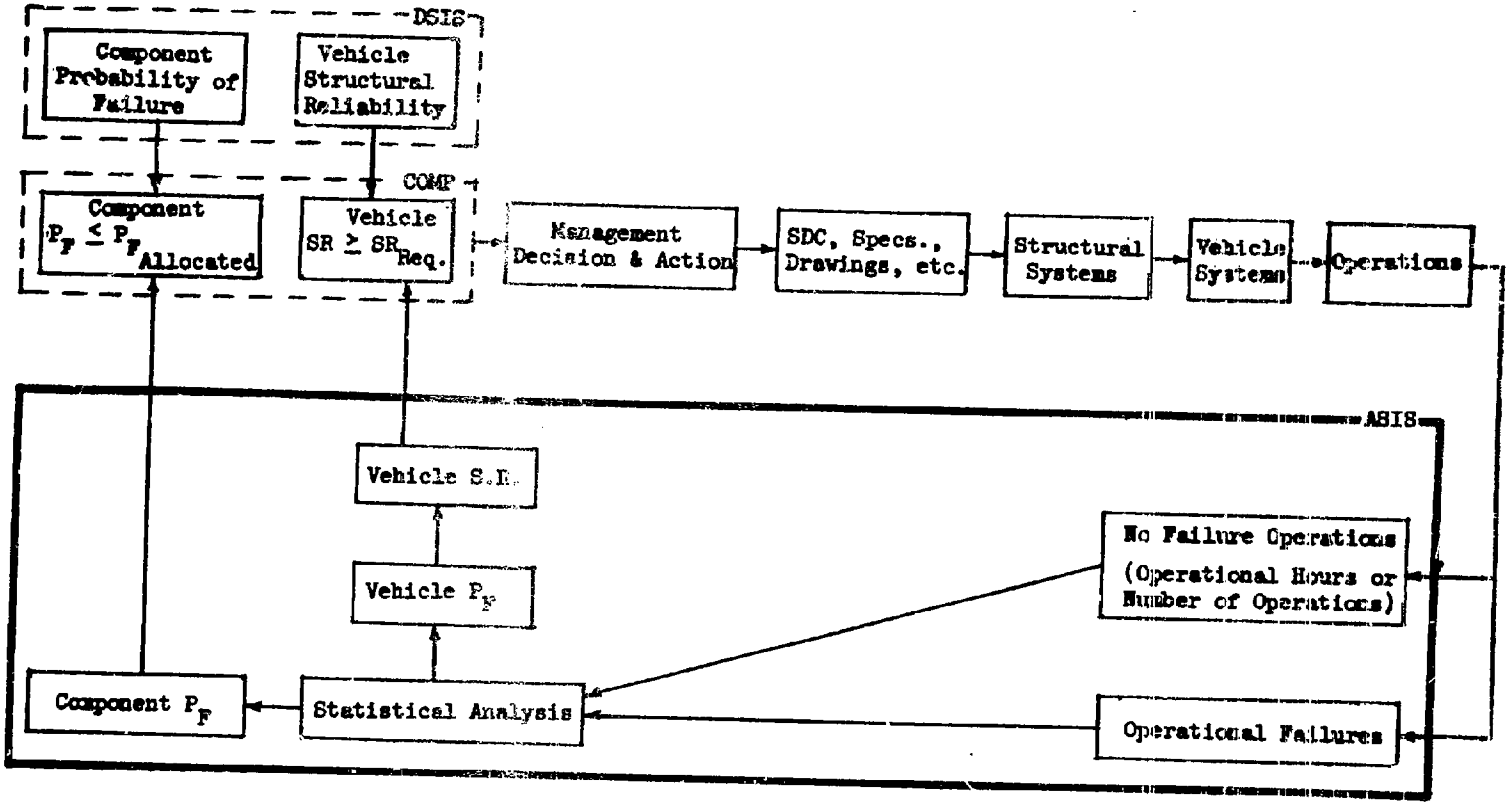
The Operational Failure Stage of the ASIS in the Purely Statistical Structural Reliability Design System, as shown on Figure 21, must necessarily perform a different function than does the same segment of the Present Structural Design System, as shown on Figure 16. The principal difference is that the investigating group will find it almost impossible to determine a "cause" for any failure. Determination of a cause implies a discrete action that is incompatible with the concept of the randomness of the parameters affecting a structural reliability analysis.

Consider the situation where a failure occurred at a flight condition that had been predicted to occur in one-in-a-hundred (or one-in-a-million) vehicles. Can the user who operated the vehicle at that condition be assigned the responsibility for causing the failure? If the vehicle failed at a load that only one-in-ten-thousand vehicles should fail at according to the analysis, can a decision be made that something is wrong with the structure? Since there is a continuous and smooth variation in the probability of occurrence of each strength and load condition, how can a dividing line be drawn to separate the permissible from the impermissible?

Based on this reasoning, the information resulting from operations must be associated with the statistical analysis. As shown on Figure 21, information on the number of failures that have occurred during operations can be analyzed relative to the number of successful operations to predict the probability of failure and the vehicle structural reliability. The value determined for one or two failures at an early stage in the life of the operational system is not very significant in deciding whether or not the structural system is fulfilling the desired state requirements.

c. Other System Functions

Functions other than the DSIS and ASIS would be the same in the Purely Statistical Structural Reliability System as they are in the Present System. However, the previous discussions have noted some of the difficulties in obtaining information on which to base the many decisions necessary in using any system.



STRUCTURAL RELIABILITY ASIS
(OPERATIONAL FAILURE STAGE)

FIGURE 21

SECTION III

EVALUATING THE PRESENT (FACTOR OF SAFETY) STRUCTURAL DESIGN SYSTEM AND A PURELY STATISTICAL STRUCTURAL RELIABILITY SYSTEM

3.1 INTRODUCTION

Section II of this report describes the extension of Draper's informetics concept to the structural design problem. Considerable discussion, couched in informetics terms, is presented in Section II, aimed at developing an understanding of how the Present (Factor of Safety) Structural Design System functions. Additional discussion is presented to illustrate, in an informetics framework, how a Purely Statistical Structural Reliability System functions.

The purpose of Section III is to convert this understanding into an evaluation of the merits and the problem areas associated with the two structural design systems outlined in Section II. In turn, this will serve as a basis for the critique of individual papers dealing with structural design criteria problems. These critiques are presented in Section IV.

3.2 GENERAL

An evaluation of any system requires an understanding of the purpose of that system and a measure of how well the system accomplishes its purpose. A structural design system is defined very broadly in this paper. It includes far more than just the structural design criteria. It includes the state of the art affecting strength and loads analysis. It includes the drafting room procedures that affect the checking of the structural drawings. It includes the government material specifications and it also includes the know-how of materials producers. It includes fabrication techniques in the shop and it includes maintenance techniques in the field. It includes the pilot's flight handbook and it includes the pilot training syllabus. In short, a structural design system includes everything that has an interface with the structural system (commonly called the airframe or the hardware), and everything that has a bearing on whether the structure survives or not.

It is recognized that such a broad definition of the structural design system is not universally accepted. It is acknowledged that there are jurisdictional problems in any design organization that inhibit control by the structures organization of all things that affect the structural system. Nevertheless, it is necessary in any evaluation of a structural design system to recognize the existence of these problems. One measure of the effectiveness of a system is how well it copes with these interface problems. Therefore, the evaluation developed in this report will not be inhibited by any preconceived ideas limiting the prescribed field of responsibility for the structures organization.

a. Functions of a Structural Design System

The fundamental purpose of any structural design system is the creation of an operational structural system that will enable the vehicle to satisfactorily perform its mission. The desired structure does not simply occur. It is the result of many management decisions that trigger actions in many processes leading to the final product. The making of decisions is the key element in the procedure.

The basis for evaluating any structural design system must be the consideration of how effectively decisions are made and implemented. As shown on Figure 9, the basis for these management decisions must be the definition of the Desired State of the structural system and the determination of the Actual State. Hence, the evaluation becomes largely an evaluation of the Desired State Information System (DSIS) and the Actual State Information System (ASIS). It is assumed that, if the correct information is presented to the management, the correct decision will be forthcoming.

b. Standards of Evaluation

From an understanding of the crucial elements in a structural design system, standards for evaluating various structural design systems can be established. The following three considerations will be used in this report as the basis for the evaluation:

1. How effectively does the structural design system define the Desired State?

2. How accurately can the Actual State be determined?

3. How early in the design and deployment cycle of the operational system will any discrepancies between the Desired State and Actual State be disclosed?

A discussion and amplification of the meaning of these standards for evaluating structural design systems will be accomplished in the remainder of this report. This will be done as the evaluation proceeds for the two systems under consideration.

3.3 PRESENT (FACTOR OF SAFETY) STRUCTURAL DESIGN SYSTEM

The structural design system that is used currently in the design of almost all aerospace structures is described in Section II. The generalized functional diagram showing how the present system operated is shown on Figure 10. Section II explained the function of the various segments of the Present System as shown on Figure 10. Evaluation of the Present System will be conducted as established in the previous subsection.

a. Evaluation of Desired State Information System

Both a strength and a weakness of the Present Structural Design System reside in the procedures that function as the DSIS. The Present System represents an eminently practical system. It has been used for the design

of aerospace vehicles for years with generally satisfactory results. The structural design system could not have been so satisfactory unless it had the inherent capability to define the Desired State in such a way that it could be expressed as a contractual requirement. More important, designing structural systems to achieve the Desired State defined by the typical structural design criteria has resulted in vehicle systems that have been generally satisfactory in their structural performance. The structural systems of aerospace vehicles have deservedly won the reputation of being the most reliable of all the vehicle subsystems.

Unfortunately, there have been enough structural failures so no one can be complacent. There are indications that new trends in structural design, both in materials and in configuration, will introduce problems with which the present structural design system cannot cope. Some of these problem areas will become evident as the discussion proceeds.

In the present structural design system, the Desired State of the structural system has been expressed in two different ways. The first is related to the failure rate of the operational system. The second is related to the so-called Margin of Safety (M.S.). The manner in which each of these considerations contributes to the definition of what the structural system should be is discussed next.

(1) Structural Integrity

One of the desired qualities for structural systems often has been called structural integrity. Since there is almost universal agreement that this is desirable, Structural Integrity has been introduced as the starting point of the Desired State Information System on Figure 10. Unfortunately, structural integrity is not a very precise concept. It means all things to all people, so it is not a suitable quantity on which to base a structural design system.

(2) Reasonably Low Failure Rate

It is believed that the meaning ascribed to structural integrity by most people is a reasonably low failure rate. This is shown in the DSIS box of Figure 10. The connection to the Structural Integrity box is shown as a dotted line because there is no direct, definable relationship between the two.

Establishing a quantitized value representing an acceptable failure rate has always had an attraction for many of those concerned with structural design problems. At least as far back as 1954 during discussions of a special panel of the NACA Subcommittee on Aircraft Loads,[18] the concept was being considered. At that time representatives of the commercial transport industry took a position that any structural design system based on a failure rate or probability of failure would be unacceptable. A principal concern was for the legal implications of deliberately designing for some probability of failure, no matter how small. In case of an airline catastrophe, they would be very vulnerable to legal action. This would be in contrast with their position under the present system where they can show they have fulfilled their legal obligations if they have complied with government

regulations such as FAR 25. A more recent exposition of the problem was presented by Stieglitz[19] at the Fifth Reliability and Maintainability Conference. He notes that "The use of numerical goals requires the establishment of an acceptable risk, leading immediately to the question of the moral acceptability of any goal other than a zero fatality rate." Stieglitz concludes with the opinion "that the use of numerical safety goals is not morally justifiable, would present serious legal problems, and is not practicable from the standpoint of being either predictable or demonstrable."

The kind of thinking characterized by this previous discussion undoubtedly has been a major factor why failure rate or a structural reliability number have never been integrated into present structural design criteria. Despite the fact that acceptance of a non-zero failure rate is an anathema to many, the practical decisions that have been made in the past emphasize the fact that a zero failure rate is not truly the goal. If it were, how could anyone justify not using a 2.0 or a 10.0 factor of safety instead of the conventional 1.5? Certainly, increasing the factor of safety by some large amount would reduce the failure rate by some undeterminable amount but obviously somewhat closer to zero than it now is.

In this respect, actions speak louder than words. A significant number of catastrophic structural failures have occurred to military fighter-type aircraft over a span of years. It is estimated that somewhere between one-in-ten and one-in-one-thousand fighters have failed structurally in the past. The incidence of failure on transport aircraft is less than this but certainly much greater than zero. In the past quarter century, transport structural failures number in the dozens. The numbers of vehicles involved are in the tens of thousands. The rate is not likely to be better than one-in-ten-thousand. Certainly, the true figure must be between one-in-a-thousand and one-in-a-million. It should be understood that this failure rate does not include only those accidents listed in official records as structurally caused. If the pilot pulls too hard on the elevator control, developing a load factor beyond the structural capability of the vehicle, the failure may be listed as pilot error. The fact remains that, if the structure had been twice as strong, the failure would not have occurred.

This portion of the discussion can be summarized by stating that there is some undefined level of structural failure for various types of aerospace vehicles that is acceptable. The acceptance is indirect and is expressed by inaction in changing structural design criteria after an accident occurs. Philosophically and practically, this is a very good system for all concerned.

(3) Generalized Structural Design Criteria

The upshot of this system is that there is no direct connection between the Desired State of a Reasonably Low Total Failure Rate and the Generalized Structural Design Criteria. For this reason the connection is shown as a dotted line on Figure 10. As a result the only direct control of the Generalized SDC is Management Action instigated by a Management Decision as illustrated on Figure 10. In turn, the Management Decision is influenced by two functions. The first represents the Subjective Considerations noted on Figure 9. A decision on the requirements can be made

completely arbitrarily by the appropriate authority in the customer's management organization. Generally, such decisions are made on the basis of what would be considered good judgment. Many considerations that are ill-defined or undefinable must be integrated to arrive at a decision. In major questions involving SDC, a consensus is usually obtained in the customer's organization. More often than not, industry personnel meet in committees to review SDC decisions and recommend appropriate changes. Nevertheless, the final decision on generalized SDC, such as MIL-A-8860 and FAR 25, is an arbitrary one. The criteria is what it is because someone in authority says it is.

Typically, changes to criteria already in use are triggered by a failure or series of failures that are considered to be "too many." The structural design criteria used for most aerospace designs have developed largely in response to specific problems that have occurred in the past. This is the second function mentioned earlier that determines Management Decisions.

Functionally, the impetus for a change starts with the decision by an investigating group identifying the "cause" of an accident. This leads to a decision on whether the cause was structural or non-structural. If non-structural, no corrective action involving the SDC is necessary. If the cause is structural, the corrective action may be to change the SDC; or it may be to change some manufacturing or quality control procedure.

One more source of change to the SDC may stem from an explicit change in the assignment of responsibility. A simple example of this type of Management Decision was the incorporation of special requirements for access doors fastened with quick-action devices. A number of years ago, a series of incidents occurred with doors of this type coming loose in flight. Initially, the decision was to improve the performance of the line mechanics and inspectors to be sure the fasteners were properly tightened before flight. This, in effect, was a decision that the cause was non-structural, so no action was taken to change the SDC. As time went on, it became obvious that the problem was not being solved on the flight line. A new decision was made to change the SDC to require that the structure tolerate and survive some loose fasteners. The division of responsibility is still arbitrary but at a different level than originally. The present requirement, set forth in MIL-A-8861,[20] states that any one fastener along any critical edge of the door must be considered to be unfastened and the door must not fail under the appropriate flight loads. The arbitrariness of the decision rests in the transfer of responsibility for preventing the failure from the line maintenance organization to the structural organization. However, if more than one fastener is loose, the responsibility remains with the line maintenance organization.

One further consideration that is a factor in evaluating the present system is the decision implicit in no action. Since the generalized SDC in effect at any given time represents the distillation of the answers to all the problems of the past, it is assumed to be adequate to define a new structural system in the absence of any evidence to the contrary. Thus, there is no motivation for the individuals responsible for the SDC specification to make changes too quickly and no condemnation for failing to institute a change until the evidence is overwhelming.

By the same token, it becomes very difficult to anticipate problems and make SDC changes before such action is forced by physical evidence of failures. Reductions in criteria requirements are nearly impossible to achieve. Since most requirements are the response to past problems, the acceptability of the reduction or elimination of the requirement is contingent on proof that the problem will not recur. Such proof is nearly impossible to generate. The difficulty in eliminating requirements is compounded by the fact that many instances of apparent elimination of a problem have occurred in the past only to have the problem arise again to confound the experts. There is a natural reluctance on the part of all concerned with establishing SDC to be placed in such an untenable position. As a result, it is much easier to avoid "rocking the boat."

The fundamental problem area in establishing structural design criteria for the Present (Factor of Safety) Structural Design System is that there is no identifiable objective that the SDC is intended to satisfy. The Present SDC is principally the evolutionary result of reaction to past problems.

(4) Vehicle Structural Design Criteria

The Vehicle Structural Design Criteria represents the conversion of the Generalized SDC into SDC applicable to a particular vehicle system. Such parameters as maximum speed and limit load factor are defined as specific numbers. As shown in Figure 10, Management Decision can result in a vehicle specification that establishes deviations or additions to the requirements of the Generalized SDC. These are the results of negotiations between customer and contractor. In many cases, such deviations represent a response to new problems that have arisen but which have not yet resulted in modifications to the Generalized SDC.

In many cases, no Generalized SDC is available for particular classes of vehicles. In such cases, it is necessary to develop the Vehicle SDC "ab initio" without benefit of any guidance from a Generalized SDC. This is both an advantage and a disadvantage. There is greater flexibility in tailoring the SDC to the peculiar needs of a particular vehicle system. On the other hand, experience has shown that program managers, both in the customer and contractor organizations, may be unaware of some of the structural problems that have occurred on similar vehicles in the past. A Generalized SDC controlled by a central organization group tends to reflect a broader knowledge of all the potential problems.

However it is arrived at, there must be some formulation of the structural requirements for a particular vehicle. Even when the same organization has the responsibility for formulating the requirements and implementing them, there should be a formal documentation of the requirements. This documentation for the structural system is usually known as the structural design criteria. If the requirements are not documented, there must be some informal understanding of what is expected of the structural system. The fact that the SDC can be changed as often as Management Decision decrees does not negate the fact that there is an SDC extant at all times in the development of a vehicle system. The Vehicle SDC in the Present Structural Design System has all the advantages and disadvantages ascribed to the Generalized SDC.

(5) Design Conditions (Limit)

The requirements established by the Vehicle SDC are transformed into discrete conditions that the structural system must sustain. The connection from the Vehicle SDC to the Design Conditions (Limit) is shown dotted on Figure 10. This is done because the determination of these design conditions is typically accomplished as part of the Analytical Design Stage in the ASIS. To illustrate this significant point further, consider what would happen if the maximum speed an airplane could attain in a dive were erroneously calculated. The Desired State of the Structural System would be to show a positive M.S. for the loads associated with the erroneous velocity. If the airplane could easily exceed the calculated dive velocity, the structure might fail, even though achieving the Desired State. This would be equivalent, in Draper's control system analogy,[2] to having the directional heading measured by a compass and always having that heading fed into the system that determines the desired compass heading. In such a case, there never would be a discrepancy between the desired heading and the actual heading. Likewise, there is no independent relationship between the Vehicle SDC and the Design Conditions.

One consideration that will aid in the development of Structural Integrity, regardless of the manner in which the Design Conditions are established, is the transformation of these Design Conditions into Operational Limitations, as shown on Figure 10. In the above case of a miscalculated dive velocity, the consequences of the error are minimized if the permissible operational conditions are consistent with the Design Conditions and if the Operational Limitations are effectively transmitted to the vehicle user.

The numbers representing the Design Conditions, right or wrong, become the controlling parameters in defining the Desired State of the Structural System. In evaluating the Present System the availability of discrete numbers must be considered as an advantage. There is no uncertainty as to what conditions the vehicle should survive. This is shown on Figure 10 as a situation of Zero Failure at Limit Condition. If a failure should ever occur at limit conditions or less, there is no question of the "cause" of the failure and the assignment of responsibility provided such failure is within the specified operational limits and which is a region considered to be safe and permissible. Thus, the user of the vehicle cannot be held responsible. The responsibility for the failure necessarily resides somewhere in the structural system. This unequivocal assignment of responsibility has been associated often with an indication that the present system is practical and administrable.

(6) Factor of Safety

Agreement on the meaning and function of the Factor of Safety has b[illegible] something less than universal, ever since the concept was introduced in [illegible]. Many engineers consider that it was the ratio of ultimate to yield stress for the aluminums and steels common at that time. Others consider it is an ignorance factor. In References 4 and 5, the concept was developed that the factor of safety served two purposes. One was to provide a strength level sufficiently above the limit conditions so that failure would "never" occur at the limit conditions unless there was an understrength condition <u>caused by</u> a gross, rectifiable error in designing, fabricating, or maintaining

the structure. The second purpose of the factor of safety was to provide some overload capability beyond the specified limit conditions, so that the structure would not fail unless the user grossly exceeded the specified operational limitation.

The present structural design system does not achieve either of these possible objectives directly. All that can be ascribed to the Factor of Safety in the present structural design criteria is that it is an arbitrary number that defines the relationship between limit and ultimate loads. In turn, the ultimate loads control the required strength level of the structural system.

The Factor of Safety (F.S.) for aircraft has been 1.5 for many years. In recent years, the F.S. for missiles and spacecraft have differed from 1.5 in many instances. Since there is no definitive objective inherent in the Factor of Safety, there is no standard of judgment to determine whether the assorted values currently used for F.S. are correct or not. The only basis for such an assessment is whether or not there are "too many" failures. Even if long experience in the use of a particular F.S. discloses that there are "too many" failures, the F.S. does not necessarily need to be raised. An alternative possibility is to increase the severity of the Design Condition (Limit). The possibility of an infinite number of arrangements of limit conditions and Factor of Safety is the source of much of the controversy over the proper choice of Factor of Safety. Either school of thought can be right or wrong. Either a high F.S. and low limit conditions or low F.S. and more severe limit conditions can define a structure that will be satisfactory. It is one of the weaknesses of the present structural design system that the choice cannot be made rationally and "proved." It may be overstating the case, but the management decisions that control the Factor of Safety are made principally on the basis of subjective considerations, including the predilections of the persons involved.

(7) Design Ultimate Loads

The Design Ultimate Loads that are a vital part of the ASIS are derived from the Design Conditions (Limit). However, the derivation is not a direct process that can be considered an independent part of the Desired State Information System. As was the case with the definition of the Design Condition (Limit), so it is with the Design Ultimate Loads. These loads are calculated as part of the ASIS operation. Limit loads are calculated for the conditions designated as Design Conditions. These limit loads are multiplied by the Factor of Safety to obtain the Design Ultimate Loads. Figure 10 shows that the loads analysis becomes the direct source of the Design Ultimate Loads that define the desired strength of the Structural System. Therefore, a dotted line connection is shown between the Design Conditions (Limit) and the Factor of Safety to the Design Ultimate Loads.

(8) Positive Margin of Safety for Design Ultimate Loads

The Margin of Safety (M.S.) is shown on Figure 10 as one of four parameters that affect the Management Decision on a Structural System. The Margin of Safety represents the increment in actual strength of the system over the required strength as defined by the Design Ultimate Load. The M.S. is typically expressed as a decimal fraction. Actually, Margin of Safety

is a misnomer. Contrary to the belief of some engineers who should know better, an M.S. of + 0.01 does not necessarily mean that the structure is "safe" in the sense that it will never fail. Likewise, an M.S. of - 0.01 does not mean that the structure is "unsafe."

The Margin of Safety is a major parameter in the control of the structural configuration. It is a convenient administrative tool. A zero M.S. represents the line of demarcation between a structure that complies with the requirements of the SDC and one which does not. All questions of compliance are related to the Margin of Safety so the parameter should be considered as a contractually important item. Whether or not a positive M.S. corresponds to a "safe" structure depends on the correctness of the SDC, the accuracy of calculation of design conditions, design loads, structural strength, and freedom from errors in the structural fabrication process.

The strength and weakness of a positive M.S. as the definition of the Desired State of the Structural System is essentially as stated above. It is the basis for an easily administrable procedure to accept or reject structural systems. It will provide a satisfactorily high structural integrity if the "new" systems are comparable to the "old" systems that resulted in the current SDC and if no gross errors are made in implementing the SDC requirements. However, the structural system that has no negative M.S. does not have any definable level of structural integrity. In fact, where the "new" structural system involves significant departures from the characteristics of the "old" systems, the "new" system may develop an unsatisfactorily high failure rate even while complying with the SDC and showing positive M.S. for all structural components.

(9) Zero Failure at Limit Condition

The last of the four functions that define the Desired State in the Present SDC is that there should be Zero Failures at Limit Condition. This situation does not get quite as much attention as the M.S. for ultimate loads, probably because the condition is usually realized automatically. Since the Design Conditions (Limit) form the basis for Operational Limitations, there is a general acceptance that it is "safe" to operate the vehicle up to these limitations. Therefore, if a failure ever does occur at limit condition or less, the user cannot be held responsible. The corrective action must involve the structural system. Thus, there is a direct correlation between any failure of this type and the Desired State of Zero Failure at Limit Condition. A single failure is an indication that the Actual State is not as desired.

This zero failure rate makes a very administrable requirement and one that is easy to definitize in a contract. The disadvantage of this function as a measure of the Desired State is that the only feedback that is available to determine whether the Actual State equals the Desired State is the fact of failure and the conditions at the time of failure. This is certainly an unsatisfactory tool for measuring the Actual State. The indication of an unsatisfactory state cannot be given until a failure has occurred. This is obviously too late in most situations. So, the fact that the analyses and tests that constitute the ASIS provide no early indication of the Zero Failure at Limit Condition must be considered a disadvantage.

As previously stated, a Positive Margin of Safety for Ultimate Loads usually provides the desired Zero Failure at Limit Conditions. However, if the Factor of Safety is reduced significantly below 1.5 or if materials with a large strength scatter are used, the zero failure rate does not automatically follow. One of the weaknesses of the Present Structural Design System is that there is no provision for solving this problem.

b. Evaluation of Actual State Information System

One of the major reasons the Present (Factor of Safety) Structural Design System has been so enduring is that the procedures for determining the Actual State have been very easy to implement. Thus, the information needed to formulate Management Decisions is readily available. At every stage in the design and development of the vehicle system, an unequivocal answer can be generated as to whether the Structural System complies with the SDC requirements; that is, whether the Desired State is attained.

It was pointed out in Section II that there are three basic levels or stages in the ASIS of the present system. These are the Analytical Design Stage, the Test Stage, and the Operational Stage. An evaluation of how well each of these stages contributes to the determination of the Actual State will be performed in the sections following.

(1) Analytical Design Stage

The Analytical Design Stage was described in Section II as providing the first prediction of the Actual State of the M.S. The calculated M.S. is the end result of the chain of calculations. These start with the Calculation of Design Conditions, then on to the Loads Analysis, the Strength Analysis, and finally the Strength Analysis Report. The calculated M.S. is documented in the Strength Analysis Report. This provides the formal means to perform the function indicated for the Comparison as as shown on Figure 10.

The process of calculating the Margin of Safety is thoroughly familiar to and well understood by most structural engineers. This is obviously an advantage of the present system. Any change that is made should possess indubitable advantages before the change is implemented. The procedure is relatively simply and quantity of calculation is limited. The M.S. that is the end product of the calculations may be disputable but any such disputes can be resolved by appropriate tests. In this respect the Present System fulfills one of the prerequisites of a good system as established by Coutinho.[16] He notes that "there must be a system of timely and simple tests to confirm the predictions. The shorter the elapsed time between prediction and verification, the greater the pressure for accuracy in the prediction." Structural analyses have been subject to this pressure for greater accuracy for years.

Unfortunately, these advantages are balanced by two disadvantages. The first is that, despite the fact that most of the calculations are accurate, occasional errors are committed which result in the true M.S. being negative rather than positive. The second problem is that periodically a situation arises where the structure has a true positive M.S. for all the

specified conditions yet the structure will fail in service, because of an error in defining the design conditions.

A further disadvantage of the Present System is that the Strength Analysis gives no direct information on the state of the Structural System for the two parameters other than M.S., established as part of the DSIS. The Desired State of Zero Failure at Limit Condition is not analyzed at all in the typical strength analysis. The fact that a positive M.S. usually indicates that a structure will be free from failure at limit conditions or less does not mean that the Present System really makes provision for such a requirement. Besides the problem of gross analytical errors large enough to cause failures at less than limit conditions, there is a problem that is expected to be more prevalent in the future. This is the situation that structural designs with relatively large strength scatters will not necessarily have the zero failure rates at limit conditions and reasonably low total failure rates that have been the characteristic of conventional structures. References 3, 4, 5, 6, and 21 have documented the fact that the failure rate of structures with large strength scatters, or coefficient of strength variation (γ_s), may be orders of magnitude higher than the rate for more conventional structures. In the past the situation has been controlled by avoiding the types of material and structure that give rise to the problem. The positive M.S. is no real guarantee that the structure will be satisfactory. Current trends indicate that structures with large strength scatter will necessarily be more prevalent in the future. Hot structures typically have large scatters in strength. New materials such as graphite, beryllium, and molybdenum tend to be brittle and thus erratic in their strength. Extremely large shell structures such as used in current and projected boosters have large scatter in their buckling coefficients. Long, slender columns, such as might be used in truss structures in the zero-G environment of large space stations, are quite variable in their failing strengths.

It is quite possible that the users of the Present Structural Design System could find that they have innocently backed into a dangerous situation without any apparent change in the satisfactory practices of the past.

(2) Strength Test Stage

The first of the three branches of the ASIS that involve testing is the Strength Test Stage. The Strength Test covers many types of test. It includes the well known static test that has been a major factor for years in developing satisfactory structural systems. It also includes other types of tests such as fatigue tests, drop tests, shake tests and acoustical tests. In fact, as used here, Strength Test includes any type of test whose purpose is to "prove" the strength of the structure.

For all practical purposes, the Strength Test can be considered to be the final arbiter of the true M.S. of the Structural System. If the structure fails at less than ultimate load, it must be redesigned no matter what the calculations predict. Usually, after a premature test failure occurs the analysis is changed to show, with 20-20 hindsight, that the failure was to be expected. The test requirements are easy to administer. If the structure sustains the load, this constitutes proof of compliance. It is an easy resolution of any differences of opinion that may have existed over the Strength Analysis.

In order to understand the real advantages and disadvantages of the Strength Test as a part of the total structural design system characterized by Figure 10 it is desirable to understand what is the true function of the test. Reference 21 notes that "the function of testing is to act as an error discloser, not a reliability 'prover.'" It also points out that "a structural system that does not pass a test can be rejected on the basis of that test even though the passing of a test, in and of itself, provides little proof of the level of structural reliability attained by the system."

In terms of the M.S. the single test does not prove what the true analytical value for the M.S. should be. Remember that the M.S. represents the relationship between the material allowable and the ultimate load. If the allowable is higher than the load, the M.S. is positive. Remember, also, that the allowable is typically the strength exceeded by 99 percent or 90 percent or "most" of the material. An error could exist in the analysis and the stress at some point on the structure could be higher than the allowable. Although this corresponds to a negative margin, the test structure might survive because the particular test article might happen to equal or exceed the average strength. Thus, the single test does not determine exactly what the true M.S. really is.

On the other hand, the test is a nearly perfect discloser of gross errors. For instance, Reference 53 shows that a structure, whose mean strength is at limit load instead of above ultimate and whose strength scatter is small, has a 10^{-24} probability of passing the usual strength test to ultimate load. It is somewhat immaterial at this level whether the actual failure occurs at 65 or 70 percent of ultimate load so that the apparent M.S. is minus 0.35 or minus 0.30.

The previous discussion is valid only if the strength scatter is small, as is customary in past aerospace structures. If large scatters become as prevalent as the earlier discussion in the Analytical Design Stage indicated would be likely, then there develops a significant possibility that a structural system whose mean strength is at limit load will actually pass the Strength Test at ultimate load. In such a case, the apparent M.S. would be positive even though the true M.S. is appreciably worse than minus 0.33. In the example given in Reference 53 the true M.S. for a structural system, whose mean is at limit load and whose coefficient of strength variation is 0.20, is minus 0.53. Under the assumptions of this particular example, a structure with this grossly false indication of the true M.S. will be accepted once in every 160 tests. This inability to disclose analytical errors when strength scatter is large must be considered one of the shortcomings of the Present Structural Design System.

Another obvious shortcoming of the Present Structural Design System has already been indicated to be the situation that a high level of Structural Integrity does not necessarily follow even if the true M.S. is positive. The mere fact that the structure passes a strength test does not guarantee satisfactory structural performance. The conditions tested are selected largely on the basis of the Strength Analysis, so that an error of omission in overlooking a critical condition in the analysis will be perpetuated in the test.

Another problem area in validity of the Strength Test as an indicator of the true M.S. is the accuracy of the test simulation. Test techniques have evolved over the years to the point where they were well understood and generally satisfactory for the structures that were conventional up to about 10 years ago. In recent years new considerations have complicated the problems of test simulation. Hot structure obviously represents one of the more critical problems in simulating operational conditions. Meteoroid impact is another simulation problem affecting space vehicles. As discussed in the Analytical Design Stage some of these new situations do not lend themselves to a definition of their Actual State by an evaluation of the Margin of Safety.

(3) Flight Test Stage

The Flight Test Stage of the ASIS fulfills an extremely important function in the Present Structural Design System. It plays a major role in confirming the loads on which the M.S. of the structural system is based.

The Strength Test is almost always based on loads determined in the Analytical Stage as shown on Figure 10. Thus, the M.S. determined in the Strength Test Stage is subject to discrepancies from the true M.S. There have been many cases documented where the measured flight loads were significantly different than the analytically predicted values. The accuracy of the final flight test measurements is usually very high. Although it is not at all unusual to obtain erroneous data from the initial instrumentation and calibration, the problems are resolved in most cases during the conduct of the flight loads test program. The capability to repeat flights as necessary is a major reason for the high final accuracy of the measurements. Any time that differences are found between measured and analytically predicted values, the instrumentation is immediately suspected. Accordingly, the instrumentation is reviewed carefully and the calibration is rechecked until the cause for the discrepancy is found. Because the other organizations concerned are reluctant to change their analytical values, the flight test organization usually has to prove conclusively that there is no significant instrumentation error in their final results.

Another beneficial aspect of the aircraft flight loads test program is the capability to explore the entire operational regime, extending the limits of the exploration in small increments. This permits a continuous evaluation of the significance of the attained results and a halting of further flights any time the results obtained indicate a serious overload situation is developing.

One of the weaknesses in the application of the same structural design system to spacecraft and launch vehicles is that the very nature of these operations inhibits any repetitive testing procedures. Furthermore, almost every flight is an operational flight directed towards completion of missions other than structural testing. Consequently, the deliberate operation of a space vehicle to limit conditions for test purposes is extremely rare. This inevitably degrades the accuracy of the determination of the true M.S. of space vehicles to a lower level than has been customary with aircraft.

Another problem area is that some critical conditions may not be explored during the Flight Test Stage. The Electra problems[22] are an

example of this situation. There is no sure cure for this problem, but widespread dissemination of knowledge of such problems should do much to insure that they do not happen a second time.

Still another weakness of the Flight Test Stage in developing vehicles with high Structural Integrity is the near impossibility of testing the vehicle beyond the specified limit conditions because of the risks involved. As a result, no information is obtained on possible non-linearities or non-proportionalities in the flight loads beyond the limit conditions. Most structural failures of aircraft occur during operation beyond the specified limitations. Non-linearities may unwittingly reduce the capability of the vehicle to sustain overload to a point where excessive failures may occur.

A by-product of the flight loads test program is the first demonstration that the Structural System is capable of meeting the second Desired State shown on Figure 10. The operation of the test vehicle to limit conditions during the flight loads program effectively demonstrates the capability of the entire vehicle system. If there are any gross understrength or overload situations that have not been detected previously, they may show up during the final structural demonstration flights.

(4) Proof Test Stage

As discussed in Section II the need for a Proof or Acceptance Test resides in the fact that some structural systems have a significant possibility that an individual structure may be grossly understrength compared to the average strength. Typically, proof tests are considered necessary for pressure vessels where welding presents problems in obtaining perfect reproducibility from one vehicle to the next.

An advantage of a proof test is the extremely simple concept involved. If the structure is loaded to or slightly beyond the limit condition, it either sustains the load or it doesn't. Failure during the test is proof positive that the structure in question would not attain the Desired State of Zero Failure at Limit Condition. Furthermore, no Management Decision is really required to upgrade the Structural Integrity by removing the defective article from the operational Vehicle System. The proof test failure automatically does this.

The principal disadvantages of the Proof Test Stage as an ASIS are twofold. First the Proof Test is usually conducted for one particular loading condition. Weakness under other conditions may exist but not be disclosed by the simple proof test. Also, the proof test is most meaningful in situations where a discrete maximum load occurs as in pressure vessels. When a spectrum of maximum loads occurs as in the case of gust loads, a proof test is a less effective tool.

The second disadvantage of the Proof Test is that the test operation itself may damage the structure so that second and subsequent loads may be more likely to cause failure. Some boosters are known to have suffered from this problem. The difficulty is compounded when repeated proof tests are conducted during the manufacturing process and subsequently during maintenance checks. A minor disadvantage is the difficulty in determining

whether a proof test is necessary. This tends to be a judgment decision. As an example, consider the case of one booster vehicle which had been in production for a considerable period of time. No proof test failures had occurred and it appeared possible that the proof test requirement should be eliminated. While this suggested change was under consideration, several proof failures occurred. Investigation showed that an apparently minor change in welding technique had occurred. It is quite conceivable that, if the failures had been delayed to a slightly later period, the decision to eliminate the Proof Test might have been implemented. In such an event, the defective articles would have entered the operational inventory, only to fail at a later, more crucial time.

(5) Operational Failure Stage

The Operational Failure Stage is the final indication of the Actual State of the Structural System. Like the other stages, this stage represents an imperfect procedure for the measurement. An operational failure is obviously an undesirable instrument for measuring the Actual State. No matter what failure rate is considered acceptable, no one really desires a failure. The Desired State Failure Rate is really the maximum rate permissible. A lower rate is hoped for. Nevertheless, when an operational failure does occur, it would be negligence not to use the available data as an indication of the Actual State of the Structural System and to make Management Decisions that would tend to prevent similar failures in the future.

In many situations the cause of the failure is obvious and so is the corrective action. In other cases the Probable Cause Determination is rather subjective. The choice between a non-structural cause involving an overload on a satisfactory structural system or a properly operated and loaded structural system failing by virtue of an understrength problem is sometimes rather arbitrary. An interesting example of how two disparate decisions were made in somewhat similar circumstances is embodied in the requirements of MIL-A-8861,[20] Paragraph 3.1.15. (This discussion expands a discussion of the same problem on page 45 of this report.) The specification requires that "doors and other coverings shall remain in place under design ultimate flight loads if 10 percent of the fasteners are unfastened or if one quick release fastener selected at random on each edge of a door or panel secured by these fasteners is unfastened." This criterion was adopted after a series of incidents in which access doors came loose during flight. Presumably, the initial determination was that the cause was non-structural. The management decision was that the Total Failure Rate was too high (again, "too high" is a rather nebulous concept), but the cause was attributed to overload on the structure due to preventable carelessness on the part of line mechanics and inspection personnel. The Management Action as part of the System Control shown on Figure 10 would be to issue new instructions and perhaps to change maintenance manuals, clarifying the proper procedures for securing quick-action fasteners. There probably were several attempts at preventing the occurrence of loose fasteners, but the situation continued. It is inconceivable that this problem could not have been solved some day, given enough time and money. Instead, a Management Decision was formulated that required the structure to tolerate the loose fasteners without any failure. This decision instantly converted what had been a non-structurally

caused failure into a structural failure. As a result, the Management Action now becomes a change in the Structural Design Criteria. This, in turn, defines a new Desired State. Now, the ASIS is measuring the Actual State against a different standard.

Just to emphasize the subjective nature of the decision involved, a different decision was once made in a similar situation. A commercial airliner was designed with a hinged leading edge for access to controls and plumbing along the span of the wing. The leading edge was held in place with fasteners of the type being discussed. On one occasion the leading edge was opened up by the crew for servicing. Unfortunately, the leading edge was closed and a few of the fasteners installed to temporarily hold it in place. Subsequently, the airplane took off before anyone remembered to tighten the remainder of the fasteners. Almost as soon as the plane was airborne, the leading edge folded over. The loss of lift and excessive drag on one wing caused the plane to crash. In this case, the cause was determined to be non-structural and maintenance and inspection procedures were revised. No change was ever made in MIL-A-8861 comparable to that for small doors, even though the problem is essentially the same.

The problem that is inherently troublesome in using Operational Failures as a major function in the ASIS is that it is an after-the-fact function. The very availability of failure data means that something less than perfection is the Actual State of the moment. The situation can be corrected but it would obviously be preferable to prevent the failure in the first place. Use of operational failure data is certainly an imperfect solution to the problem. In spite of this, Structural Design Criteria has evolved almost exclusively in response to problems disclosed by failures.

The alternative of using operational successes to measure the Actual State of a structural system is even less meaningful. The problem has been identified by some as the problem of "random success." At the failure rates usually considered to be even marginally acceptable for aerospace vehicles, a long string of successes does not contribute much to the information regarding the Actual State of the Structural System.

c. Evaluation of Other System Functions

Many of the functions of the other systems outlined in Figures 9 and 10 are outside the traditional scope of the structural design system. Nevertheless, they affect the operational results obtained with the structure and cannot be ignored.

One consideration that may be considered an advantage by some but a disadvantage by others is that the Desired State specified in the Model Specification and the Structural Design Criteria represents the minimum requirement. This means that, once the Management Decisi[illegible]ade in the Customer's organization, all Contractor organizations mus[illegible]t the same requirement. There is no provision for optimization of [illegible]equirement with respect to weight, cost, reliability of other systems, e[illegible]. The optimization that is currently practiced by most structural analysis a[illegible] design organizations is with respect to providing the lightest weight or least costly structure that complies with the minimum requirements. On this basis there

is room for competition between different contractor organizations, yet there is a discipline in this competition since all are constrained to optimize to the same base. There is a "moment of truth" when the structure must survive the design ultimate load. From the user's standpoint, there is some question whether it would be acceptable to have two competing vehicles performing exactly the same mission but with one having a significantly lower strength level than the other. It seems logical that each vehicle design should have the same minimum capability so that, if they were flown side-by-side, the user would not be required to restrict the operation of one more than the other. On the other hand, the competitive pressures to minimize weight and cost will insure that the structural system does not exceed the minimum requirements by very much. Thus, the Present Structural Design System tends to insure that all structural systems are just barely on the high side of the minimum.

Another consideration that must be listed as a problem area is the many state-of-the-art items in areas such as material processing, fabrication, inspection, and pilot training that affect the total failure rate without being controlled in any positive fashion. As a simple example of this effect, consider the following World War II problem. All airplanes of that era were designed for the vertical tail loads associated with an uncoordinated turn maneuver. For the type of flying that was considered normal up to that time, the criteria was satisfactory. Sometime after combat operations over continental Europe were initiated with B-17's, a series of vertical tail failures occurred. The failures were precipated by the practice of fish-tailing the bombers at the natural yawing frequency in an effort to avoid flak from the ground. Very large yaw angles were developed, well beyond all previous experience. If pilot training and pilot's handbooks had specifically prohibited the maneuver, the failures might never have occurred. If the pilot's training syllabus had specifically included practice in the fishtail maneuver, the problem probably would have been discovered and corrected before the bombers went into combat.

Inspection procedures are expected to prevent defective material from appearing in operational vehicles. The Present Structural Design System makes implicit assumptions on the effectiveness of these inspection procedures. When new fabrication techniques are developed, no specific provisions are incorporated in the Present Structural Design System to modify the SDC if the new techniques are not as consistent as previous techniques. The difficulties that have been experienced in various procedures for bonding materials is a case in point.

Figure 9 shows that software functionally influences the operational system. An example of this might be the dispatching procedures used by an airline. The success of the weather forecaster in vectoring transports away from turbulent areas may have an appreciable effect on the number of structural failures. A parallel situation occurs in the launch operations control of a space vehicle launch. The predicted winds aloft become part of the input that determines the go-ahead for a launch. The more accurate the meteorological prediction, the less likely the launch vehicle will encounter excessive wind shears.

A major disadvantage of the Present Structural Design System is that there is no explicit provision for defining the interfaces between structural

and non-structural systems with an allocation of responsibility for accomplishing specific functions. This forces decisions affecting structural design in the Present Structural Design System to be made on an ad hoc basis rather than from a predetermined set of principles.

d. Evaluation of Present System Performance

The merits and demerits of the Present (Factor of Safety) Structural Design System have been discussed at length in the previous sections. One of the major advantages of the Present System is associated with the generally high level of structural integrity possessed by structural systems designed under present procedures. Other advantages of the Present System are administrability and ease of implementation. The principal disadvantage of the present system is associated with the fact that there is no clearly identifiable, quantitative objective that the Present System is expected to satisfy.

(1) Structural Integrity

The principal advantage of the Present (Factor of Safety) Structural Design System is that it works. It has provided a generally high level of structural integrity for the aerospace vehicles designed in the past 30 years. Occasional instances of structural problems have been resolved and generally have not reoccurred.

The system has had the capability to provide suitable requirements for a wide range of missions including military fighters, commercial transports and space vehicles. Each of these classes of vehicles has a level of structural reliability appropriate to its mission. Although this level is not quantitized, it is generally accepted that commercial transports have a higher structural reliability than military fighters. The present system has developed in such a way that the proper level for each class of vehicle has been provided indirectly.

The very act of defining limit conditions helps to insure structural integrity. These limit conditions are usually translated into operational limitations. They obviously inhibit the exceedance of the design limit conditions. If this were not done, the vehicle user would have no guidelines to safe and unsafe operational regimes. By the same token, the operational limitations provide guidelines for determining the cause of any structural failure. Corrective action can be taken only if the problem to be corrected is defined. If a failure occurs at the specified limit condition or less, the operator cannot be responsible for causing the failure. The structure must be grossly understrength. But, if a failure occurs while the operator is grossly exceeding the specified limitations thus using up the strength increment provided by the factor of safety, the cause of the failure must lie with the operator. With the cause established, it becomes apparent either that changes in the mode of operation are necessary or that improvements in the design and fabrication of the structure are necessary. It is a vital element in the present system that the operational limits and required strength are deterministic. This allows control of each, which is essential to good structural integrity. It provides an exact measure of how much

overloading by the operator must be tolerated by the structure. And it provides an exact measure of how much understrength a structure must be before it is intolerable and obviously the result of an unacceptable mistake in the structural system. The Present System has the inherent capability for self-correction to prevent repetition of structural problems.

The Present System has the great advantage that resides in tried and true things. It is thoroughly familiar to all personnel involved in designing, fabricating and using structural systems. There are undoubtedly many considerations affecting structural integrity that are not defined in structural design criteria and other specifications. Such considerations may be covered by other requirements without anyone realizing the necessity for such provisions. These considerations are also part of the present system.

The Present System derives much of its capability to provide structural systems with high structural integrity from a successful integration of test requirements into the total structural design system. Strength tests such as the conventional static test together with shock, vibration and various forms of fatigue tests have proved to be an excellent discloser of errors in the analytical design of the structure. Flight loads tests and similar tests provide the same validation of the loads analyses involved in structural design. The higher the degree of certainty of error disclosure, the higher the structural integrity of the system.

Proof testing is beneficial to structural integrity where repeatability in the fabrication process is a problem as in the case of welded pressure vessels. The proof test comes close to providing absolute certainty that the structure can survive the specified limit condition although it provides no assurance that the structure can tolerate operational overloads. The proof test provides an increment of assurance for a structural system that is already fundamentally sound.

(2) Administrability

An important consideration in the utility of any structural design procedure is the administrability of the procedure. This is not a technical consideration but is a very practical consideration that is often overlooked by proponents of new procedures. In order to incorporate structural requirements into the contract defining a vehicle system, there must be some way to administer the contract. This consists principally of establishing procedures to decide whether to accept the hardware resulting from the structural design requirements. Since rational people will disagree over the interpretation and implementation of the provisions of a contract, there must be a proof-of-compliance procedure that can resolve such disputes. Proof of compliance inevitably means that the requirements must be quantitized in some fashion that is demonstrable. The Present (Factor of Safety) Structural Design System is eminently suited to proof of compliance requirements at every step in the design and development of a new structural system.

Administration of the generalized structural design criteria such as MIL-A-8860[23] is simplified by the fact that no action is required until the need for a change becomes overwhelming. It is a fair assumption and one that is usually acceptable to all concerned that structural design criteria and other specifications represent all applicable past experience and are pertinent to future requirements until proved otherwise. Maintenance of the status quo requires no agreement and, when the need for a change becomes very obvious, agreement is almost automatic. This situation is easy to administer.

The deterministic nature of the Present System contributes to its administrability. There are many situations such as the static test where any uncertainties are removed by the either-you-do-or-you-don't nature of the test. There can be no equivocation in such a situation. Such tests also furnish a convenient basis for proof of compliance requirements.

The format of the requirements lends itself to easy administration. Definition of limit conditions is tied to mission requirements. The limit conditions have the characteristic that, right or wrong, they represent agreed-upon conditions for the design of the structural system. If the requirements prove to be wrong, both parties to a contract are protected by the need to renegotiate any new design requirements that become necessary during the development of a new system.

The Margin of Safety represents a convenient quantity for defining the amount the strength is above or below the required strength. It also has the virtue that it is understandable by non-specialized personnel. It provides such people with a psychological feeling of security in the absolute safety of a structure even though the specialist knows there is no such thing as absolute safety.

To meet the need to assess responsibility and to take corrective action in case of failure, it is common practice to establish an investigational group to determine the cause of a failure. The decisions of such a group are facilitated by the characteristic of the Present System that any failure at limit condition is unequivocally the responsibility of the structural system and any failure at ultimate load has to be the result of overloading the system beyond the permissible limits. Determination of a cause of failure simplifies the administration of the corrective action.

(3) General Comments

The Present (Factor of Safety) Structural Design System is well known to a very large group of structural designers and analysts and to the users of the vehicle systems incorporating structural designs developed in accordance with the requirements of the Present System. Despite the fact that there are some problem areas associated with the Present System, the familiarity of the Present Design System should not be abandoned for the unknowns of a new design system unless the advantages of the new system are overwhelming. If there is a choice between modifying the Present System to eliminate the problem areas or adopting a radically new procedure, the choice should be heavily weighted in favor of modification.

However, modifications are made with great reluctance. There is an understandable tendency to resist changing structural design criteria and other design procedures. This is both a strong point and weakness of the Present System. Trivial changes are not likely to be introduced so there is a desirable steadiness in the requirements. However, it is difficult to introduce desirable changes until the force of circumstances, such as catastrophic failures, demands a change. Reduction or elimination of a requirement is nearly impossible since it is nearly impossible to prove that a situation that once called for the requirement will never occur again in the future. There is an understandable reluctance on the part of the individuals concerned to make decisions reducing requirements. Caution is justified by the number of instances where such a reduction was regretted Consequently, structural design requirements tend to increase in severity over a period of years. The use of some function other than catastrophic failure to motivate changes in the Present System would be very desirable.

The Present System does not explicitly define the interfaces between the structural system and other systems. There are many inherent assumption built into the Present System. Such things as a continuance of the present state of the art and an assumption that the user will continue to operate new vehicles as he did those of the past are typical of these implicit assumptions. Since the interfaces are not explicitly defined and since responsibility for particular actions is not fixed, the assumption is periodically in error and it becomes necessary to accommodate the Present System to new situations. The parameters important to structural integrity should be identified and an unequivocal responsibility for controlling the parameters should be assigned.

(4) Problem Areas

Lack of a clear-cut definition of what the structural system and thus the structural design system is expected to achieve is at the root of all problems related to the Present (Factor of Safety) Structural Design System. This problem is exemplified by the desire to have high structural integrity without being able to define or measure structural integrity. As a result criteria have developed by reaction to problems, not as a logical approach to an objective. This is not to say that the Present System does not produce Structural Systems with high structural integrity. But it does it indirectly — and sometimes inconsistently. As a result, structural design criteria tend to become rigid and sacrosanct. The requirements begin to acquire the characteristic that they exist for their own sake rather than to accomplish a specified purpose. This characteristic is typified by the lack of a statement of objective in MIL-A-8860.[23] It is difficult to question rationally the requirements since there is no logical basis for such questioning.

Since structural design criteria tend to evolve on an ad hoc basis in response to some kind of difficulty, there is an implicit assumption that the criteria will provide a satisfactory structure if the conditions affecting the new system are comparable to those of the past. Since aerospace vehicle design is constantly expanding into new fields, the implicit

assumption of the status quo provides a built-in bias for encountering future troubles. If the objective were more definitized, it might be easier to marshal all available knowledge to meet that objective rather than to satisfy a requirement simply because it's a requirement.

As a specific example of the problem, it is pointed out that the chances of accepting a deficient structural design increase markedly when the coefficient of variation in strength (the strength scatter) goes up. In the past we have avoided this possibility by using materials and configurations that have small scatter. This was accomplished by using "good aerospace quality" materials, ductile materials operating over a relatively narrow temperature range. Circumstances involved in designing for operation in extreme environments are forcing the use of brittle materials at very high temperatures. This results in strength scatters that would not have been acceptable in the past. The Present System has no mechanism to cope with this problem.

Another problem area in the Present System is that the existence and proof of a positive Margin of Safety does not guarantee that the structure will be satisfactory. In particular, if there are considerations in the new structural system that were absent from previous designs, such as a large strength scatter, the "new" structural system may be quite inadequate even while showing a positive M.S. A specific example is the small operational capability that might be provided if the loads are non-linear beyond limit conditions. It is very easy to show a case where the structure could withstand loads 50 percent greater than limit loads yet have less than 10 percent capability for exceeding limit L.F.

There is no direct provision in the Present (F.S.) Structural Design System to arrive at the desired condition of Zero Failure at Limit Condition. It has been achieved indirectly in the past. Future changes in the direction of a lower Factor of Safety and larger strength scatters will change the situation. In the future a zero failure rate at limit conditions may not be so automatic.

Associated with the two previous problems is the problem of the function of a strength test as a discloser of error in the strength analysis. This function has been performed with great accuracy in the past. In the future, this accuracy of error disclosure will be degraded if structures with large scatters in strength become necessary to fulfill future mission requirements.

Validation of the loads analysis will become more of a problem in the future. In particular, a one-shot operation such as a space vehicle is not amenable to a thorough investigation of the loads in all flight regimes. Aircraft flight loads programs, by nature of the capability to repeat flights as often as necessary, are very thorough. A space vehicle or a ballistic missile will not be instrumented for flight loads very often. Such vehicles will rarely be programmed to attain the design limit conditions. The result can only be some degradation of the contribution of the Flight Test Stage to the development of structural integrity in the vehicle.

The use of the well-known 1.5 factor of safety is not justified on the basis of accomplishing a definable objective. As a result when it is suggested that the factor of safety be reduced, there is no basis for rational decision. Good judgment can be and is used in making such decisions, but one value cannot be "proved" correct and another wrong.

Over a significant range of values for the Factor of Safety, any number could be justified. It is pointed out on page 47 that the F.S. serves two purposes. It provides a margin for grossly overloading the vehicle beyond the specified operational limitations and it provides for a gross under-strength in the structure. Considering the overloading question first, it is apparent that either a 40 percent overload or a 50 percent overload could be considered a gross violation of the operational limitations. The operator of the vehicle would be just as hard pressed to justify a 40 percent violation as a 50 percent violation. By a simple executive decree, any vehicle failures at 40 percent overload could be charged to operational causes. A determination of "pilot error" is a common reflection of this. The corrective action in such case is effectively predetermined to be to correct the operational practices that led to the overload but not to change the structure. Obviously, the more the Factor of Safety is reduced the more dubious it is to charge an operational exceedance with responsibility for a structural failure. It seems obvious that it would be unreasonable to inform a pilot that it was "safe" to operate an airplane at 6.0 G's but gross negligence to operate it five percent beyond at 6.3 G's. This would correspond to a factor of safety of 1.05.

By the same token, it would represent a gross departure from the expected strength if a structure failed at 67 percent (the inverse of 1.5) of the design strength. Such a failure could not possibly be construed as a typical random variation in fabrication. Such a loss of strength could only come from some discrete and gross error such as an incorrect dimension or omission of a process like a specified heat treat. With a 1.5 F.S. any understrength sufficient to cause failure at limit conditions would have to result from a discrete error that would be corrected rather than from a random variation that the structure would be expected to survive. Essentially the same statement could be made if the F.S. were 1.4. The understrength at limit condition would be 71 percent which still must result from a gross error. On the other hand, a F.S. of 1.05 would require that a failure at 95 percent of the design value would have to be called a gross error while failure at 100 percent would be called normal and expected. Such a decision could be justified only under the most unusual conditions.

The problem rests with the fact that the transition from the obviously-too-large to the obviously-too-small Factor of Safety is gradual and imperceptible. A choice of a specific Factor of Safety implies that any lesser value is wrong. It must be accepted that a smaller F.S. is less good but not wrong. The problem is compounded by the fact that an identical structural strength can be specified by increasing the severity of the required limit conditions while reducing the magnitude of the Factor of Safety. The dilemma is how to make a rational choice of Factor of Safety in the face of all the subjective considerations affecting F.S.

One of the principal problem areas of the Present System is that there is no appropriate way to define a factor of safety for some of the major problem areas of modern structural design such as fatigue and extreme temperatures. The Present System is predicated on design for conditions that are static or quasi-static. Most aircraft designs prior to 1950 did not require explicit consideration of these new problems. In terms of defining the Desired State for structural systems affected by fatigue or high temperatures, the relationships between the desired Structural Integrity and specific requirements in the Generalized Structural Design Criteria are more indirect than ever. Furthermore, the difficulties involved in determining the Actual State of structural systems operating in these new environments are compounded. In particular, the error disclosing capability of the presently available tests in fatigue and thermal environments does not appear to be as powerful as the well-known static test. There is a need to review the procedures involved in these problem areas to find better ways to define the objective and to measure the degree of compliance with that objective.

3.4 PURELY STATISTICAL STRUCTURAL RELIABILITY SYSTEM

The general characteristics of a structural design system based on purely statistical structural reliability considerations is described in Section II. In developing and describing the functional outline for this type of system, the discussion in Section II necessarily indicated some of the problem areas. These will be reviewed in the evaluation, together with other considerations that affect the usefulness of a Purely Statistical Structural Reliability System.

a. Evaluation of Desired State Information System

As indicated in Section II, the Desired State Information System is simplicity itself. As shown on Figure 17, the Desired State is defined by two quantities. The first of these is the Vehicle Structural Reliability and the second, the Component Probability of Failure. In Draper's paper, he indicates that Desired State definition begins with Imagination and Desires. Literally, anyone can choose any number from zero to one for the desired structural reliability. The choice, without any necessity to explain why, becomes the Desired State. In the same vein, anyone can allocate a value for the maximum probability of failure for a given structural component.

The problem is somewhat more difficult if the Desired State Values for structural reliability are to be selected on a rational basis. However, it is not anticipated that this problem offers any insurmountable difficulty if a structural reliability design system should be generally adopted. Reference 5 recommends three levels of structural reliability, 0.99, 0.9999 and 0.999999, for three levels of risk that might be acceptable for different types of vehicles. There is some thought that the 0.99 figure might be associated with fighter-type aircraft and 0.999999 with transport aircraft. Reference 5 recommends 0.9999 as the choice for a standard space vehicle. These recommendations are certainly not expected to be universally acceptable. They do illustrate that desired levels of structural reliability can be quantitized in some logical fashion.

One problem in establishing structural reliability (S.R.) as the desideratum of structural design is the question of precisely what is meant by structural reliability. The term is glibly mouthed by many but rarely is there a real comprehension of what it means. There must be an understanding of whether the value is to be based on the assumption that all individuals and organizations affecting the S.R. perform as they are assumed to perform. In other words, should the probability of error be included in the definition of structural reliability?

Then, there are three orders or reliability to be considered. The first is the structural reliability of an individual vehicle. As each vehicle is produced, it has an inherent strength. Some vehicles fabricated to the same specifications as others will have a low strength. Some will have a high strength. The lower-strength vehicle will have a higher probability of failure than the higher-strength vehicle. This certainly does not mean that all low-strength vehicles will fail before all high-strength vehicles; but, undeniably, the probability of failure is higher. Thus, each individual vehicle as it stands ready to operate has a structural reliability that is associated with that particular vehicle alone.

A second order of reliability involves the reliability of a group of nominally identical vehicles, typified by all the vehicles of one particular model. The structural reliability of the model is that determined by the probability of success of one vehicle taken at random from all the vehicles. In a manner of speaking, the model structural reliability represents the average structural reliability of all the individual vehicles of that model. On this basis the model structural reliability may be quite high yet an individual vehicle of that model may have a low structural reliability. The one is no guarantee of the other.

The third order of structural reliability involves the general reliability of all aerospace vehicles designed in accordance with a particular procedure. This might be thought of as the structural reliability of the complex of systems. The actual structural reliability of some models will be higher than that of others even though they are intended to be the same. The model structural reliability bears the same relationship to the complex of systems as the individual vehicle structural reliability bears to the model structural reliability. The structural reliability of the complex of systems corresponds to the structural reliability of all aerospace vehicles from the Wright Brothers' Flyer to the Apollo. This structural reliability represents the average of all systems taken together. Since it is an average value, an individual system may be very low compared to the average. The discussion in Section 2.3 of Volume II amplifies this concept.

To oversimplify the situation, one might imagine that, out of one million systems, all but one system had perfect structural reliability (that is, the probability of failure is zero). The millionth system could have a zero reliability (that is, all the individual vehicles in that system would be certain to fail). In this case the reliability of all the systems taken as a group is 0.999999. This would be small comfort to the user of the millionth system which has zero reliability.

This discussion of the meaning of structural reliability is intended to show that choice of a structural reliability number to represent the Desired State must be accompanied by an explicit definition of what the term represents. Otherwise, the structural reliability number is meaningless.

Despite these detail difficulties, a vehicle structural reliability requirement can be considered to be capable of fulfilling the first evaluation standard listed on page 42 to effectively define a Desired State. The second part of the desired state definition, as shown on Figure 17, is the definition of Component Probability of Failure. This function has the same difficulties as the Vehicle Structural Reliability Requirement in defining a precise meaning for the parameter. The Component Probability of Failure has an additional problem of definition that is not generally recognized. The question is whether the required minimum probability of failure of a component should be considered independently of the probability of failure of other components.

The philosophy of allocating a share of the total vehicle probability of failure to each component is basic to most of the proposed structural reliability approaches that have been published to date. Such allocation of probability carries with it the implicit assumption that the failure of each component is a random event, independent of the failure of any other component. This assumption of independence undoubtedly developed as an outgrowth of the adaptation of electronic reliability technology to the structural problem. However, the assumption provides a false basis for establishing a desired maximum probability of failure for each component in a composite structure. Those who base their formulation of the structural reliability problem on the assumption of independence display a lack of understanding of the real modes of structural failure that must necessarily bring into question the credibility of their entire approach.

Bouton [3] noted that "the allocation of a proportionate share of the total unreliability to each component, as advocated by so many, is statistical nonsense." Reference 3 presented some figures showing how the total probability of failure varied with number of components for some simple situations. It did not present any formal analysis of the problem. McLaughlin[24] presents a rigorous proof of the principle involved in a similar situation and in Reference 25 he extends the rigorous proof to the case of multiple components subject to a common loading spectrum.

In summary, a Vehicle Structural Reliability Requirement and Component Probability of Failure provide a feasible basis for establishing the Desired State of a structural system. However, more rigor must be applied to the definition of the two functions than has been common in past analyses of structural reliability. Otherwise, the numbers generated in the solution of structural reliability applications to structural design problems give a completely false representation of the true situation.

b. Evaluation of Actual State Information System

The functions involved in determining the Actual State of a structural system in a Purely Statistical Structural Reliability System were described

in Section II. The same stages involved in the Present System are included in the Structural Reliability System. Their evaluation parallels the evaluation of the Present System in Section 3.3 of this report, but the problems in establishing an Actual State Information System for a Purely Statistical Structural Reliability System are vastly different.

(1) Analytical Design Stage

The functional diagram of the Analytical Design Stage of the ASIS for a Purely Statistical Structural Reliability Stage is presented as Figure 18 in Section II. All of the problems of calculating the loads for specific operational conditions and the internal loads or stresses for those conditions are the same as in the Present System. However, the magnitude of the computational effort is far greater because of the many combinations of load and strength that must be considered for the statistical analysis. In addition, the probability of occurrence of all of the various operational conditions must be calculated and then converted into the probability that the local load or stress for an individual component will exceed various values. It is a moot question whether any of the papers presently available on the subject have realistically considered the magnitude of the total computational effort involved in computing the probability of failure of a reasonably large selection of components and the structural reliability of the vehicle as a whole.

Granting that the calculations can be accomplished if sufficient manpower and money are available, the computations are still subject to all the errors in the loads and strength analyses of discrete conditions as discussed in the evaluation of the Present System in the previous sections of this report. Added to this will inevitably be occasional errors in predicting the spectra of operational conditions and other probabilities contributing to the calculation of probability of failure.

Reference 8 documents the magnitude of the problem when it shows that the theoretical structural reliability calculated under an assumption of no error in the strength analysis may drop from 0.999999 to approximately 0.9 when a reasonable error function is introduced. This error function is based on the error frequency documented in Reference 17. Surely, this amount of error associated with just one of the eight functions shown on Figure 18 as affecting the Calculated Component Probability of Failure must increase as error probabilities are introduced for the other functions. Although no proof is given, Figure 2 of Reference 4 shows qualitatively the slow growth in reliability as various tests are completed and the magnitudes of the calculation errors are reduced. The conclusion must be drawn that the Analytical Design Stage of the Purely Statistical Structural Reliability System, even as the comparable stage in the Present System, is not by itself sufficiently accurate to serve as the measure of the Actual State of the Structural System.

(2) Strength Test Stage

A functional outline of the Strength Test Stage of the ASIS in the Purely Statistical Structural Reliability System is shown on Figure 19.

This outline effectively exposes an important consideration that undoubtedly has been a major factor in the reluctance of experienced engineers to embrace the structural reliability approach in designing structural systems. This consideration has been overlooked by most proponents of structural reliability procedures.

The problem is that the Strength Test as presently constituted does not result in any direct indication of the Actual State of the Structural System. If the Desired State is going to be defined in statistical terms, so also must the Actual State. A single Strength Test has no particular value as an indicator of the structural reliability or component probability of failure. As noted in the Evaluation of the Present System, the Strength Test serves as the final arbiter of the true M.S. of the Structural System. A corresponding capability simply does not exist for the test operation in a Structural Reliability System. Any feasible test procedure where one or two test articles are tested for a limited number of discrete conditions could not possibly delineate the statistical parameters associated with the structural system under investigation As Grose says in Reference 26, "funding of test programs to prove reliability numbers like 0.99999 would bankrupt the nation." He points out that we "desire something (accurate numbers) which is economically unobtainable."

Coutinho and Tiger make some pertinent observations in Reference 16 that are applicable to the structural reliability problem. They state that "the quantification of reliability...is a necessary prerequisite for expressing (it) as (a) contract requirement and as a condition of hardware acceptance. Such quantified requirements must be expressed in terms that can be demonstrated in qualification and acceptance tests.... The objective of the reliability prediction during the conceptual stage is to justify the selection of a design which will meet the reliability qualification tests."

In the Present System the successful support of the Ultimate Design Load constitutes a very practical means for defining proof of compliance that leads to hardware acceptance. A Purely Statistical Structural Reliability System is deficient in this respect.

Incidentally, the ability to focus attention on the true objectives of a structural design system and the function of various procedures in that system demonstrates the power of the informetics concept in evaluating the various approaches.

The previous section documented the fact that analytical procedures alone are not accurate enough to determine the reliability of a structural system. The present section indicates that the typical Strength Test will not add significantly to the definition of the Actual State.

There are other problem areas in the determination of the statistics on the loads and the operational conditions. All things considered, the Purely Statistical Structural Reliability System is not a practical system unless some way can be devised to demonstrate that the structure complies with the contractual requirements. Without this capability it is not feasible to write a definitive contract for the design, fabrication and construction of an aerospace vehicle.

(3) Flight Test Stage

A functional outline of the Flight Test Stage of the ASIS in the Purely Statistical Structural Reliability System is shown on Figure 20. The function of the Flight Test is comparable to that of the Strength Test. The results of the Flight Test can only define necessary revisions in the loads analysis. This, in turn, may revise the calculation of the loads spectra and the calculation of probability of failure. The Flight Test does not and cannot produce information that directly affects the determination of the Actual State. The transfer function that determines the local loads for a given operational condition can be validated. The loads spectra are still completely dependent on the frequency of occurrence of the various operational conditions. The Flight Test Stage can contribute very little to the statistics of the load spectra. Even if statistical data on loads are collected during the Flight Test Stage, they are not usually applicable to the normal operational usage of the vehicle. It is virtually impossible to generate information during flight test operations that will lead to the acceptance or rejection of a design on the basis of compliance with a structural reliability requirement.

(4) Operational Failure Stage

A functional outline of the Operational Failure Stage of the ASIS in the Purely Statistical Structural Reliability System is shown on Figure 21. The function of the ASIS in the Purely Statistical design system is markedly different than the corresponding stage of the Present System. It is pointed out in the discussion of the Operational Failure Stage of the Present System in Section II that one of the most important uses of failure information is in the determination of the probable cause of the failure. Establishing a cause of failure is obviously the first step in management action to prevent such a situation from reoccurring.

In the Purely Statistical Structural Reliability System it is impossible to designate a cause and to pinpoint the responsibility. Cause and responsibility are deterministic concepts. They are incompatible with the concept of randomness that underlies the Purely Statistical approach. If a situation occurs that was predicted to occur only once in a million times, the parties concerned can claim that the occurrence was a random manifestation of something that is to be "expected" occasionally. If the situation repeated itself, it could still be claimed to be a random situation even though it is now a one-in-a-trillion situation. In a Purely Statistical Structural Reliability System, there is no mechanism available to provide the basis for making a firm management decision that something is wrong and should be corrected.

Mathematically, the problem outlined on Figure 21 is that the Statistical Analysis on a few failures and many non-failures inherently does not provide much meaningful information to compare with the Desired State. Any numbers calculated in such situations will have such wide confidence bands that they negate any meaningful decisions. It is difficult to visualize what has been proved about Structural Reliability if a fleet of 100 airplanes, with an expected reliability of 0.9999, have flown for one half of their scheduled life without failure. Even if the true reliability of the fleet were an order of magnitude worse than desired, there would be only one chance in twenty of a failure in the circumstances described.

The problem is that the limited data available from operational results does not contribute significantly to the capability to make decisions as to whether or not the structural system complies with the requirements.

c. Evaluation of Structural Reliability System Performance

The preceding evaluation of the Purely Statistical Structural Reliability System makes clear that the overriding problem impeding the general adoption of this system as the preferred structural design system is the impossibility of accurately determining the Actual State of the Structural Reliability of a vehicle. The Desired State is simple to define, although more care than is typical in discussions to date is needed to define the precise meaning of the Structural Reliability of a vehicle.

As noted in the previous evaluation on page 68, quantified requirements must be expressed in terms that can be demonstrated in qualification and acceptance tests. It does not appear that a Structural Reliability quantity can possibly be demonstrated in a reasonably practical procedure. Analysis alone has been pointed out as being too inaccurate to serve as <u>the</u> demonstration. A limited quantity of strength test articles cannot accurately define the Structural Reliability of the complete operational system. Also, there is too much dependence on the functions of many other systems being exactly as predicted for the strength test to be definitive of the S.R.

Since every function that has a bearing on the determination of Structural Reliability has a finite possibility of occurrence, it is impossible to designate the cause of any failure as being the responsibility of an identifiable individual or group. There does not appear to be a reasonable way to say that something that has a probability of exceedance of 0.01 is acceptable but is unacceptable if the probability of exceedance is 0.00001. More to the point, it is not possible to prove which situation represents the true probability after only one failure.

Statistical data on structural failures and successes during operational usage of the vehicle are inevitably insufficient to accurately define S.R. and to make decisions. Suppose a structural failure occurs on the 50th operational vehicle. The required S.R. is 0.99999. In such circumstances, how can a rational decision be made on whether the single failure is proof that the S.R. is less than required. There is simply no way to decide whether the failure is the rare random failure of a system whose true S.R. is 0.99999 or whether the failure is the expected (50 percent probability) failure of a system whose S.R. is 0.986.

As the direct result of the impossibility to measure the Structural Reliability of a vehicle system with sufficient accuracy, it is not feasible to write a definitive contract requiring demonstration of Structural Reliability. Without the capability to be placed under contract, the Purely Statistical Structural Reliability System is not a workable system.

3.5 SUMMARY OF EVALUATIONS

The evaluation of the Present (Factor of Safety) Structural Design System and a Purely Statistical Structural Reliability System in terms of Professor Draper's informetics concept has provided an unparalleled opportunity to dispassionately discuss the strong points and weaknesses of each system. It is hoped that this discussion will illuminate the structural design problem as it has never been done before.

The evaluation of the Present System has disclosed nothing startlingly new. The Present System is generally very satisfactory. Structural systems produced in accordance with the dictates of the Present System generally have a high degree of structural integrity. The Present Structural Design System is practical to use for design purposes and easy to administer for contract purposes. The discussion and evaluation in Sections II and III have served to spotlight many of the reasons why the Present System has been so successful. More important, it has served to indicate some areas that may become troublesome in the future.

The evaluation of a Purely Statistical Structural Reliability System has disclosed the fundamental reasons why the concept has never been extensively adopted for structural design purposes. The evaluation tends to justify the average engineer's intuitive rejection of a structural design system in which a structural reliability number is the basic requirement.

A brief summary of the evaluation follows together with recommendations for a future course of action.

a. Present (Factor of Safety) Structural Design System

Use of the Present (Factor of Safety) Structural Design System generally produces structural systems with a high level of structural integrity. Decisions on whether or not a particular design complies with the requirements are made on a deterministic basis. Provision for proof of compliance is inherent in the Present System. Thus, the Present System is very practical and easily administrable.

The fundamental problem area in the Present System resides in the fact that there is no clearly identifiable objective that the Present System is expected to satisfy. The requirements have evolved, for the most part, as a reaction to past problems. There is an implicit assumption that future structural systems will have the same characteristics as past systems. This is not necessarily a valid assumption. In particular, current trends indicate that many future systems will have a much larger coefficient of variation in strength than has been customary in the past. Also, most space vehicles will not receive the extensive flight loads testing that has been customary with aircraft. Both of these conditions tend to degrade the power of the test to disclose errors in the analysis.

Another result of the lack of a clearly identifiable objective is that there is no logic available that can resolve questions such as a request to lower the factor of safety from 1.5 to 1.4. There is great need for a criterion by which to judge such questions objectively.

In some of the newer structural design areas, such as fatigue and high temperatures, the factor of safety concept is not directly applicable to the definition of structural design requirements. There is even more need to clearly define the objectives of the structural design system for these problems than there is for the problems that the Present System conventionally considers. Coupled with the definition of an objective must be practical procedures for determining the Actual State and for proof of compliance with the stated objectives.

In situations where a structural failure does occur, the deterministic nature of the Present System permits the determination of a cause of failure, responsibility for the failure, and corrective action. However, many of the interfaces between the structural system and other systems are not explicitly defined. Therefore, responsibility for some of the areas contributing to structural integrity is not recognized until after a failure occurs.

b. Purely Statistical Structural Reliability System

The principal deterrent to the adoption of a Purely Statistical Structural Reliability System is the fact that there is no procedure for accurately determining the actual structural reliability of a particular structural design. As a result, there is no proof of compliance technique that would be satisfactory for demonstration that a contractual requirement has been fulfilled.

As a derivative of the problem of determining the value representing the actual structural reliability of a vehicle, there is the problem of determining a cause and assigning responsibility when structural failures do occur. When cause and responsibility are not determinable, neither is the corrective action.

c. General Evaluation

The Present (Factor of Safety) Structural Design System is a generally satisfactory system for the design of aerospace vehicles. However, there are some problem areas that will become more apparent as advanced missions require the use of new structural configurations and materials. A Purely Statistical Structural Reliability System is not practical for the design of aerospace vehicles. Since there is no way to accurately measure structural reliability, it is not possible to write a definitive contract requiring demonstration of a specified structural reliability.

3.6 RECOMMENDED CHARACTERISTICS FOR A STRUCTURAL DESIGN SYSTEM

It is reccmmended that the development of a new structural design system be implemented. This new system should incorporate the desirable features of the Present System but with modifications that would overcome the problems discussed in this report. It appears that the state of the art is sufficient to develop such modifications at the present time.

The modifications of the Present System should include the following characteristics:

1. Retain the deterministic type of requirements that give the present system its practicality and administrability.

2. Establish a clearly identifiable objective that would serve as a basis for judging any proposed modification to the Present System.

3. Incorporate a structural reliability goal as part of the objective. The goal should not become a requirement since structural reliability, per se, cannot be determined accurately enough to serve as a contractual requirement.

4. Develop the techniques to convert the structural reliability goal into deterministic requirements based on statistical considerations.

5. Add to the Present System the capability to deal with structural systems having large strength scatters.

6. Integrate specific problems such as fatigue and high temperature design into the total structural design system to attain the defined objective.

7. Identify explicitly the crucial interfaces with non-structural systems. Make provision for assigning responsibility for every function that affects structural integrity.

8. Utilize the concept of testing as a discloser of error in formulating design requirements.

9. Expand the analysis and understanding of structural design systems beyond the scope of the present report in order to develop a more rational basis for the necessary modifications to the Present System.

SECTION IV

A CRITIQUE OF CURRENT APPROACHES

4.1 INTRODUCTION

The evaluation of existing procedures plays a vital part in furthering the development of quantitative structural design criteria by statistical methods. Any critique of the available procedures should be based on an understanding of the purpose of structural design criteria. Such an understanding of purpose is established in Section II to meet the objectives for this investigation. An evaluation of the two basic systems is presented in Section III.

The evaluation of the two basic systems is extended in Section IV to include a critique of a group of papers concerned with the question of structural design and structural reliability. The papers selected are considered to be a representative cross section of the methods extant in the technical literature. The critique of the individual papers is based on a comparison with the two basic systems evaluated in Section III with additional analysis appropriate to the particular procedure being discussed. None of the papers selected represent methods developed to fulfill the functions of a structural design system as established in Section II. Therefore, any failure to consider these functions is no reflection on the papers or the authors.

The intent of this investigation is to develop a procedure to fulfill the structural design system functions described in Section II, utilizing the applicable features of existing methods to the fullest extent possible. The comparative critique will allow maximum possible applications of past experience.

4.2 BASIS FOR CRITIQUE

Structural design criteria is one of the elements in a structural design system. A structural design system is defined broadly as everything that has an interface with the structural system (commonly called the airframe or the hardware), and everything that has a bearing on whether the structure survives or not, as discussed in Section 3.2.

The fundamental purpose of any structural design system is the creation of an operational structural system that will enable the vehicle to satisfactorily perform its mission. The desired structure does not simply occur. It is the result of many management decisions that trigger actions in many processes leading to the final product. The basis for evaluating any structural design system must be the consideration of how effectively decisions are made and implemented.

Figure 10 presents a functional diagram showing the elements of a structural design system. As this figure shows and as discussed in Sections II and III, the basis for these management decisions must be the determination of the Actual State. Hence, the evaluation becomes largely an evaluation of

the Desired State Information System (DSIS) and the Actual State Information System (ASIS). It is assumed that, if the correct information is presented to the management, the correct decision will be forthcoming.

Coutinho and Tiger have expressed the same thought recently although not with the formality of Professor Draper's system. They stated in Reference 16 that "The quantification of reliability and other system effectiveness parameters is a necessary prerequisite for expressing them as contract requirements and as conditions of hardware acceptance. Such quantified requirements must be expressed in terms that can be demonstrated in qualification and acceptance tests which must be run prior to acceptance and payment." They also make the very pertinent observation that the "objective of reliability prediction is not prediction per se, but rather useful prediction."

Coutinho and Tiger go on to present an exposition par excellence of the Fundamentals of (Reliability) Prediction Techniques. This discourse is so relevant to the structural reliability problem that it is reproduced verbatim.

"Certain rituals from time to time become so well entrenched that they can no longer be evaluated objectively by their practitioners. It is a case of not seeing the forest because of all the trees. Some of this has occurred in reliability prediction. In order to introduce a measure of objectivity, it appears desirable to review briefly the fundamentals of engineering prediction techniques.

"Formal technical prediction always is based on a generalization of past experience, the generalization being expressed as a 'model.' To design a model, the significant parameters which capture the essence of past experience are expressed in quantitative terms (measured observations). These values are arranged in some meaningful orderly fashion so that their relationship to one another becomes comprehensible. Within the limits of the observations, these relationships are usually defined in a mathematical formula which constitutes the 'model' with which the future can be predicted within the stated limits. The validity of any model or analytical method is established by its ability to predict an event before it occurs.

"The successful application of these principles requires the use of a number of ingenious tricks. The first one is to select the significant parameters, that is, the ones which correlate positively with the occurrence of the event to be predicted. Furthermore, from a practical engineering viewpoint, the parameters should be easy to define and to measure. Lastly, there must be a system of timely and simple tests to confirm the predictions. The shorter the elapsed time between prediction and verification, the greater the pressure for accuracy in the prediction. The earlier in the design cycle that the information becomes available, the more useful it will be.

"In a complex development program the tests must be completed at a time when the design can still be modified if the validity of the prediction is not sustained. In cases where the validity of a prediction procedure

has been generally recognized over a long period of time, it may be acceptable to restrict part of the testing program to testing the validity of the design assumptions.

"These principles are not easy to apply; in fact, their application requires considerable creativity. Within this framework it is well to remember that the word 'engineer' originally denoted one skilled in the application of 'engine' or 'ingenuity.' Engineering is the art of skillful approximations, and a rough measurement of the right parameters is infinitely more meaningful than a precise measurement of the wrong dimensions."

4.3 STANDARDS OF EVALUATION

Three considerations were presented in Section 3.2 as the basis for evaluating the two basic structural design systems. The evaluation of the individual papers selected as the subjects for the critique in this section will follow these same standards. The three considerations are as follows:

a. How effectively does the structural design system define the Desired State?

b. How accurately can the Actual State of the structural system be determined?

c. How early in the design and deployment cycle of the operational system will any discrepancies between the Desired State and Actual State be disclosed?

4.4 INDIVIDUAL CRITIQUES

All but one of the papers critiqued fall in the class of a Purely Statistical Structural Reliability System. The exception is a modification of the Present (Factor of Safety) Structural Design System. In general, the evaluations developed in Section III for the two basic systems are applicable to the papers considered in this section. However, the general evaluations are extended and a detailed discussion is presented for each paper, separately. In some cases, particular comments are valid for more than one paper. Such comments are not repeated, but the discussion of one paper is referenced in the discussion of the second paper with no implication that the comment is any more valid for the first paper than for the second.

a. Purely Statistical Structural Reliability Methods

(1) Kluger

In Reference 11, Kluger presents a brief, clear exposition of the approach designated in Section II as the Purely Statistical Structural Reliability System. In the Reference 11 paper the procedure is developed as a technique "for predicting the a priori design of a large solid-rocket motor. It is postulated that the motor reliability R_m is a function of its structural reliability R_s and its performance reliability R_p. The structural reliability, which also can be termed the probability that the structure will

successfully retain the motive elements for the intended duration within the environmental envelope, is computed using the distributions of environmental stresses and material strengths." Most of the paper is devoted to the calculation of structural reliability.

As noted in Section 4.3, the first consideration for evaluation is: How effectively does the structural design system define the Desired State? In Section III it is pointed out how simple it is to establish a structural design system where the Desired State is represented by a structural reliability number. Anyone can choose a desired structural reliability number from zero to one, with or without an explanation of the basis for the choice. The problem is somewhat more difficult if the choice is to be made on a rational basis. However, it is not anticipated that this problem offers any insurmountable difficulty to design management possessing the appropriate background and experience.

Kluger suggested one basis for the choice in his discussion of structural reliability tradeoffs. However, it is difficult to see how tradeoffs could be considered in structural design criteria. In a competitive procurement situation, a minimum requirement is established and all bidders are required to equal or exceed the minimum. It does not appear realistic to consider that one contractor could be permitted to supply a less reliable system simply because the cost of meeting the minimum reliability requirement was higher than desired. On the other hand, the contracting agency might establish the level of reliability required on the basis of tradeoff studies. Once established the specific number chosen would become <u>the</u> requirement. The reliability numbers used in the examples and the range of the failure probabilities shown on the figures of Reference 11 are considered reasonable and are consistent with other suggested structural reliabilities.[5]

One problem that Reference 11 did not consider is the question of the precise meaning of structural reliability. Section 3.4 noted that there are three orders of reliability. These are the reliabilities for an individual vehicle, those for the group of nominally identical vehicles of a particular design, and the general reliability of all vehicles of all designs resulting from following the precepts of a particular design system. Kluger apparently considers only the second type of reliability, that of the group of vehicles of one particular design. Such a choice involves the implication that it is acceptable (desired) that one or more vehicles in a group may have individual reliabilities that are so low that failure approaches a certainty. This would be possible if the reliabilities of the remainder of the vehicles were sufficiently high. This is analogous to the famous story of the statistician who drowned crossing a river averaging three feet deep. To recognize that an individual structure in a group of similar structures may occasionally fail is being realistic. But to convert this recognition into permissiveness by establishing that a certain number of failures is acceptable is questionable. Just such permissiveness is established if a requirement such as a structural reliability of 0.9999 is the only requirement defined.

The common assumption characteristic of most structural reliability papers is that a structural reliability number can be used to define the

Desired State of a structural system. Although the definition of structural reliability is usually somewhat imprecise, as in this paper, there would be no great difficulty in formulating a sufficiently precise requirement for the structural reliability of a structure. The principal difficulty with the Reference 11 procedure as with most structural reliability procedures suggested to date resides in the answer to the second evaluation question from Section 4.3: How accurately can the Actual State be determined?

The most important problem impeding the general adoption of a Purely Statistical Structural Reliability System is the impossibility of accurately determining the Actual State of the structural reliability of a vehicle. Section III discusses many of the reasons why the actual structural reliability cannot be determined accurately. Reference 11 assumes that there is no accuracy problem by assuming that the calculation or prediction of structural reliability is the same thing as the determination of structural reliability.

As Coutinho and Tiger[16] point out, "In the eyes of the analyst, 'to predict' generally means 'to determine.'" Nothing could be further from the truth. In effect, Kluger and others assume that the load and strength distributions are "known" in which case the structural reliability is "known." But the load and strength distributions are not known simply because a particular analysis predicts a particular distribution. Reference 17 documents some of the errors that have been made in strength analysis in the past. Statistics are presented on the frequency of various amounts of understrength as revealed by static tests. These data have been used to show the decrement in structural reliability due to the incidence of analytical errors.[5] Results of such calculations indicate that a theoretical (no error) prediction of 0.99999 is reduced to approximately 0.9 when a reasonable error function is introduced. A comparable situation is shown on Figure 23 of this report where a "no-error" calculation of about 0.999 to 0.9999 for structural reliability deteriorates to about 0.9 when the error function is introduced. It is a simple truth that failures have occurred far more often in the past from errors of omission or commission in various loads and strength analyses than from a random variation in these functions. Any attempt at calculating the true structural reliability without considering the statistical distribution of analytical errors is an exercise in futility. Such things as error functions may not be recognized but they undoubtedly contribute to the reasons why most structural engineers intuitively reject a structural reliability number as the basic requirement for design.

This omission of any consideration of the possibility of errors in the prediction of the load and strength distributions is the principal shortcoming of the Reference 11 procedure. A few detail comments on other aspects of this paper follow. The paper correctly evaluates the problem of demonstrating structural reliability. It states that "The statistical demonstration of reliability with the customary confidence limits (90-95%) requires large sample sizes, even for moderate values of reliability target values." Then, it is noted that "The limitations of time and cost obviously prohibit such test programs." The discussion in Section III reinforces the contention that demonstration of structural reliability, per se, is not

feasible. The impossibility of demonstrating structural reliability coupled with the typical inaccuracy in calculating a structural reliability number means that a Purely Statistical Structural Reliability system such as Kluger advocates is not practical for the design of aerospace vehicles.

In the section on "Assessment of the Structural Reliability R_s," Reference 11 states two assumptions that define the basis for his procedure. The first is that "it is assumed that there are no unknown critical modes of failure." The second is that "calculation of structural reliability is based on the assumption that the failure-causing stress function and the material-resisting function are both representable by normal distributions with known means $\bar{x}$ and variances of σ^2."

The assumption that there are no unknown critical modes of failure is not consistent with known facts. The history of aerospace design from the days of the Wright brothers to the most modern spacecraft is replete with examples of failure modes that were unknown — at least to the designer — until the instant the failure occurred. Rhode[27] documented several cases where space vehicle structures failed unexpectedly. It is unlikely that there have been more than 10,000 different designs since the Wright brothers. It is certain that there have been at least 100 unexpected failures in static test or in operations. Therefore, it is inconceivable that the actual structural reliability of any given design could be considered to be greater than 0.99 when based on analysis alone (no test). High structural reliability is developed in the real design situation only by a combination of analysis and verification as described in Section II.

The assumption that the load and strength distribution situations are known to a degree of accuracy compatible with the expected structure reliability cannot be substantiated. The previous discussion made this clear. The principal reason that these unexpected failures occurred is that the mean strength or the mean load were not as predicted. A minor indictment of the assumption is the obvious impossibility of a normal or Gaussian distribution as a true representation of strength. A normal distribution, by definition, has non-zero values from negative infinity to positive infinity. Intrinsically, no structure can have a strength less than zero. Accordingly, the distribution function below zero strength must have a zero value. Since this is not compatible with the non-zero value of the normal distribution, the Gaussian assumption must be wrong over the half of the total range that lies between negative infinity and zero. It is true that the assumption of normal distribution is often a good approximation of the true distribution. However, as soon as the choice of a distribution is recognized as an approximation, the assumption that <u>the</u> distribution is <u>known</u> becomes unsatisfactory. The degree of approximation or the error between assumption and true value becomes an important and often overriding consideration in the calculation of structural reliability.

Another problem in determining the characteristics of the load and strength distribution is that most of the available data will be centered near the mean value. Experience has shown that any one of a number of distribution types (such as normal, log-normal or Weibull) could be chosen with essentially the same degree of confidence in the validity of the choice.

Yet, at the tails of the curves which are largely instrumental in determining the "no-error" structural reliability, the various distributions may be orders of magnitude apart. The approach of Reference 11 does not offer much hope for coping with this problem.

Another question arises in connection with the definition of the strength distribution. The discussion presented in Reference 11 is concerned exclusively with applied tensile stresses and the variation in the stress at which the material fails. There are many modes of failure in which the ultimate tensile stress plays a minor role. Stability failure is one example. However, even the simplified case given in the paper illustrates clearly some of the problems in the Purely Statistical Structural Reliability System. The "guaranteed" strength of a material is not a statistical property. Even though some materials properties presented in documents such as MIL-HDBK-5 are ostensibly statistically determined, in actual fact all material allowables are decided by committee action. The accepted values may or may not coincide with the values ascertained by any given material producer.

In any event, a "guaranteed" value doesn't guarantee survival of a particular vehicle. If the material should happen to be provably under-strength, the supplier's obligation would be very limited. Typically, the supplier would replace a few dollars worth of material but would assume no obligation beyond that for the loss of a multi-million dollar vehicle. Beyond that consideration, an allowable tensile stress of 215 kips would not be guaranteed by the supplier. Such a high strength in steel is usually developed by heat treating. Since this is a user process, it is not controlled by the material producer and cannot be guaranteed. There will be variations in the heat-treat process from one structure to the next. There will be variations in the heat-treat level achieved in various portions of any given structure. All of these variations add to the variation in the basic material and add opportunity for error in the fabrication process.

It is well known that pressure vessels of various types are fabricated by welding. More often than not, the weld strength is the critical element in the structure. There have been authenticated cases where the weld strength was improperly defined, causing a premature failure of the pressure vessel. There are other cases where the weld strength of a properly-made weld was correctly defined but fabrication difficulties resulted in an inferior weld after a large number of vehicles had been fabricated with the proper welding technique. Both of these situations illustrate that the material strength distribution does not necessarily represent the strength distribution of the structure.

Just as the true strength distribution may be different from the predicted distribution, so may the true load distribution differ from the predicted. The choice of stress as the parameter describing the load function illustrates a common difficulty in defining the problem. The load for the example case is the pressure in a rocket motor case. The basic question is whether the case survives or fails under this pressure. Transforming external loads to internal stresses introduces an undesirable step that opens the way to solving the wrong problem in the analysis. In this

particular example, it is assumed that membrane (hoop) failure is the principal mode of case failure. However, it is well known that in such situations the failing stress is affected by biaxial stress conditions, discontinuities, deviations from perfect spherical end closures, etc. It thus becomes impossible to predict accurately either the true applied stresses at the point of failure or the stress at which failure will occur. To simplify the problem to the extent done in this paper is to render the results of any reliability analysis meaningless. The main point to be made here is not that there are differences between the simplified analysis of the example and the true stress distribution. The point to consider is that in any analysis of a complex structure there will be such differences between predicted (calculated) and true values. The only question is in the magnitude of the differences. To complicate the problem further, there will be differences in the specific values calculated by one analyst when compared to those calculated by another. In such a situation it is impossible to determine the truth. Thus, analysis alone is not sufficient as the modus operandi to <u>determine</u> whether or not a structural system possesses a specified reliability.

The definition of factor of safety is another function discussed in this paper that should be examined carefully. (F.S. is defined as the ratio of mean strength to mean load.) A definition similar to Kluger's has been used by other authors. The question is more fundamental than might appear from a superficial consideration of the meaning of the function. First of all, this definition of the term Factor of Safety is not the same as the commonly understood definition. Certainly, every author has the right to name and define his own terms. However, the decision to change the meaning of a term that has wide-spread usage and understanding while associated with a different meaning is unfortunate. The typical aerospace structural engineer would be unnecessarily confused by such a change. Second, some of the implied meanings behind the present usage of factor of safety would be lost if the definition were adopted. At present, most engineers would consider that the factor of safety represented an increment in load beyond the limit load that the structure must be able to support. It could be shown that, in many situations, the well-known " 5 factor of safety would be grossly insufficient to produce a reliab structural system when applied to the mean load as recommended.

The factor of safety also represents an increment in structural capability beyond the operational conditions that are designated as operational limitations. Kluger's factor of safety has no direct relationship to the limit loads. As a matter of fact, as the coefficient of strength variation changed, the factor of safety would change. It would be quite confusing to operational personnel to have vehicles operated on exactly the same mission but with different factors of safety because the structural configuration was different. This might be justifiable if it were the only way to obtain the desired results from a structural design system. However, it can be shown that the present meaning of the factor of safety can be retained while introducing statistical concepts into structural design procedures. Thus, there is really no reason for introducing a change in the meaning of factor of safety.

In the discussion of Performance Reliability, Reference 11 notes that three out of one hundred simulated firing showed unacceptable average thrust and total impulse values. If just one of these three unacceptable firings happened to result in structural failure due to significant excess pressure during operations, the failure rate would approach one-in-a-hundred rather than one-in-twenty-five-hundred predicted in the example. If such a failure occurred it would be difficult to decide whether the failure resulted from "unacceptable average thrust and total impulse values" or from an understrength structure. If the first situation prevails, it means that the predicted loading distribution is not the true distribution, only the distribution conditioned on there being no "errors" in operation. If the latter situation prevails, it means that the strength situation is not as predicted.

This simple example serves to illustrate some of the principal problems involved in the adoption of a Purely Statistical Structural Reliability System. The incidence of errors in the calculation of the actual operational load distribution and in the calculation of the actual strength distribution simply must be considered to obtain a realistic reliability figure. From the management standpoint there is no way to define the cause of the failure if the firing did produce unacceptable thrust because there is no defined limitation on what is acceptable thrust. To calculate the probability of exceeding a given thrust imposes on no one the responsibility for avoiding a thrust that should be considered to be an overload. If a cause for the failure cannot be designated, corrective action to prevent similar failures cannot be taken.

To summarize this critique of Kluger's proposed procedure, it is concluded that the definition of both the Actual State and the Desired State are insufficient for use in the practical design of aerospace vehicles. Some of the detail considerations follow:

1. Lack of a precise definition of the meaning of structural reliability inhibits use of the parameter as a design requirement.

2. No basis is given for choice of a particular value of structural reliability as the desired value. Tradeoffs between structural reliability and weight and cost are not realistic as the basis for the design of an individual vehicle.

3. The assumption is made that load and strength distributions are "known." No consideration is given to the possibility that there may be errors in the various analyses, in the operation of the vehicle, and in the fabrication and maintenance of the structure. As a result the theoretical calculation of structural reliability does not truly reflect the actual reliability.

4. Testing to demonstrate structural reliability is rejected as prohibitive in time and cost. No procedure is offered to serve as a proof of compliance with a structural requirement. Without such a procedure it is impossible to write a definitive contract in terms of structural reliability.

5. Definition of the factor of safety as the ratio between the mean strength and the mean load is a gross departure from the historical meaning of the term. Inevitably, such a change in meaning will result in confusion among those concerned with implementing the structural design and with operating the resulting vehicle.

Evaluation of Kluger's procedure by the standards listed in Section 4.3 results in the following conclusions:

1. Reference 11 does not define which of the three types of structural reliability is being specified when a particular value is specified as the Desired State of the structural system. This is not a serious problem since a more precise definition of what is meant by a structural reliability value such as 0.9999 would not be difficult to add without changing the basic approach.

2. The Actual State of the structural system cannot be determined very accurately by the proposed procedure. It depends entirely on an analytical determination of failure modes, failure levels, and the strength and load distributions. It can be shown that determination of structural reliability by analysis alone is not sufficiently accurate for the level of reliability expected in most structural design.

3. There is no provision in the procedure for the disclosure of discrepancies between the Desired State and Actual State. Hence, the only disclosure will be as a result of an operational failure. Even after a failure there is no mechanism in the procedure for deciding whether the failure is truly the random failure that was predicted to occur in one-in-ten-thousand vehicles or whether the failure is the direct result of an error somewhere in the design, fabrication, inspection, operation or maintenance process.

(2) Haire

The method presented by Haire in Reference 12 is typical of his rather extensive writing and analysis on the subject of structural reliability. Haire's procedures as described in this paper are very comparable to those proposed by Kluger. The first four considerations listed on page 83 are equally applicable to Reference 12.

The fifth point is not strictly applicable since the ratio between mean strength and mean load is defined as the "reliability factor, $\overline{RF}$." Although this factor has exactly the same meaning as Kluger's factor of safety, it does not have the disadvantage of changing the historical meaning of the term "factor of safety." The difficulty in using Reliability Factor is that it is not a physically meaningful term. It represents an abstract concept. The most important objection to the adoption of a Reliability Factor function as defined is that there is no meaningful correlation between the Reliability Factor ($\overline{RF}$) and reliability. There is a question whether the parameters entering into $\overline{RF}$ are known with an accuracy sufficient to justify the Reliability shown on Figure 3 of Reference 12. Aside from that, an $\overline{RF}$ equal to 1.1 could result in a reliability of 0.999999 while an $\overline{RF}$ equal to 2.6 could result in a reliability of 0.6. It all depends on whether the coefficient of variation of reliability (C_{VR}) that is introduced in this analysis is large or small. Haire's Figure 3 shows an extremely wide range of reliability for the same Reliability Factor.

Reference 12 states that "probability distributions cannot be accurately described in the regions of extreme values." It goes on to say that "Pre-established levels of reliability should not be set as design requirements but only as design goals." Despite these acknowledged limitations in the use of the calculated reliability numbers, Haire proceeds to use reliability numbers approaching 0.999999 as though they were definitive. This is done on Figures 3 and 4, for example. On page 286, it is stated that "the reliability is in excess of 0.99999." With the data available and the incidence of errors described in Section III, it is unrealistic to say that the reliability is in excess of 0.99999. Section III notes that the true reliability approximates 0.9 when a reasonable error function is introduced into the calculations. If this be the case, then the usage suggested on page 298 of the paper becomes dubious. It is indicated that the analysis showing a reliability of 0.99994 for the first stage structure and 0.9997 for the interstage structure could and should be used as the basis for removing weight where not needed and adding where needed. In operation, the stage with the 0.99994 reliability that is presumably over-strength might fail on every flight because of some miscalculation in arriving at the loads or strength. On the other hand the supposedly less reliable interstage might never fail. A different analyst could make different assumptions (or different mistakes) resulting in the opposite decision as to where to add and subtract weight. When such a circumstance arises (as it inevitably will), this approach and other similar approaches offer no practical procedures for resolving the question and making a decision as to which analysis is correct.

Reference 12 seemingly rejects testing as a basic element in the development of reliable structures. On page 298 it is stated that "Structural loads and strengths must be described and related by statistical methods...so that only minimum reliance need be placed on test and service experience to prove designs." The logic of this statement is questionable. Inherently, the description of loads and strengths in statistical terms has no relation to the need for a test. On page 52 it is noted that the true function of testing is to act as an error discloser, not a reliability "prover." It has been pointed out on page 67 that statistical computations are "subject to all the errors in the loads and strength analyses of discrete condition" plus the

"occasional errors in predicting the spectra of operational conditions and other probabilities contributing to the calculation of probability of failure."

Formulating the analyses in the sophisticated techniques of the statistical world does not automatically make the calculations error-free, thus diminishing the need of testing as a procedure to disclose these errors. Coutinho and Tiger express the realities of the situation very eloquently in Reference 16. "Nor is this problem of confidence in the validity of a mathematical model necessarily eased by using more elegant mathematics or a more detailed analytical procedure. Mathematics is truth only within itself. We must always make assumptions about the real world and use this as the starting point in developing a mathematical model. Mathematical truth only pertains to what is between the assumptions and the developed equations. If the assumptions are wrong, the resulting equations mean nothing in regard to predicting future occurrences."

Evaluation of Haire's procedure by the standards listed in Section 4.3 results in essentially the same conclusions as those set forth for the Kluger paper on page 83.

(3) Readey

In Reference 9, Readey presents a structural reliability prediction method developed as part of a study under an Air Force research contract. Reference 9 together with Reference 10 constitutes the complete documentation of the study. Wagner, in Reference 28 which is critiqued later in this report, presents a brief summary of the procedure recommended in Reference 10. In that report, it is suggested that the procedure of Reference 9 be considered for future use. It is noted that "there remains a significant amount of method development and parameter research to be accomplished before this method can be used with the desired level of accuracy." Then, it is stated that "the level of effort expended on this development and research will determine when it will be possible to require use of this method."

The implication that <u>the</u> structural reliability can be determined and used as the basis for a specification is carried out in the recommendation for a future specification as presented on page 59 of Reference 10. In paragraph 3.3 it is stated that the "structural reliability shall be as specified in the overall requirements of the missile system." However, it has been stated throughout the present report that a structural reliability requirement is not feasible because there is no satisfactory proof of compliance technique for demonstrating that such a requirement has been fulfilled. Section 3.6 recommends that a structural reliability <u>goal</u> be incorporated as one of the objectives of a structural design system. Contractually, establishment of a goal is far different than establishing a requirement.

The fundamental difficulty in the procedure recommended in Reference 9 is that, like References 11 and 12, any consideration of the probability of analytical error in the computations is omitted. As a specific example, Reference 9 presents calculated reliabilities of 0.9906 and 0.9741 for two

different materials. It has been shown in Section III that the true reliability for similar examples approaches 0.9 when a reasonable error function is introduced into the calculations. Figure 23 of this report also indicates this same trend. Such a gross difference between the predicted and true values invalidates any decisions based on differences between predicted values that are relatively small compared to the differences between the predicted and true values.

This critique would disagree with the premise of References 9 and 10 that a structural reliability requirement should be adopted as soon as more data are available. Statistical data always represents a record of the past. Their value in predicting the future depends on whether the future "population" represented by the statistical data is the same population as the one measured during the data gathering activity. In general, this is not true for the parameters affecting the design of aerospace vehicles.

Typically, the available data are modified in some way to serve as the basis for the prediction of the future. Even using the data unchanged involves the implicit assumption that the future population is identical with the past population. This may or may not be true. As Coutinho and Tiger say,[16] "We should not assume that the mathematical relationships derived from hardware in current use will validly apply to the hardware whose reliability is to be predicted." Sections II and III and the discussions of the Kluger and Waire papers have attempted to justify the rejection of a structural reliability number as a criteria requirement, even if an unlimited amount of statistical data were to be made available.

Another concept touched on in the presentation of Reference 9 is safety factor as an ignorance factor. Such identification of the safety factor as an ignorance factor is quite common in the literature on structural design procedures. It is important to decide whether or not the structural design procedures should incorporate a provision to compensate for ignorance and, if so, how much. In this critique, the position is taken that the factor of safety has not been an ignorance factor and that future, new systems should not make specific provision for ignorance. There are many different forms of ignorance. Insufficient knowledge in the present state of the art to solve a particular problem is one form of ignorance. Unfamiliarity with the state of the art which causes an analyst to use improper or inadequate procedures is another form. It is undeniable that at various times designs that might have been adequate because of ignorance on how to arrive at the proper design have been adequate in service because of the factor of safety. To use these fortuitous circumstances to justify the factor of safety as an ignorance factor is a dubious conclusion. For one thing, any time that ignorance in the true state of affairs relative to a structural design is disclosed, the structure is modified accordingly. The ignorance is not absorbed in the factor of safety; the structure is not considered satisfactory until the effects of the ignorance are removed. For another thing, it would not be sufficient to absorb all ignorance effects even if the factor of safety were increased to 2.0, 5.0, or 10.0. There would always be some situation where the ignorance would result in greater discrepancies than any factor that might be assigned. More important, to build such a factor into the requirements would penalize all the designs where ignorance was not a consideration. This should not be done.

Evaluation of Readey's procedure by the standards listed in Section 4.3 results in essentially the same conclusions as those set forth for the Kluger paper on page 83.

(4) Austin

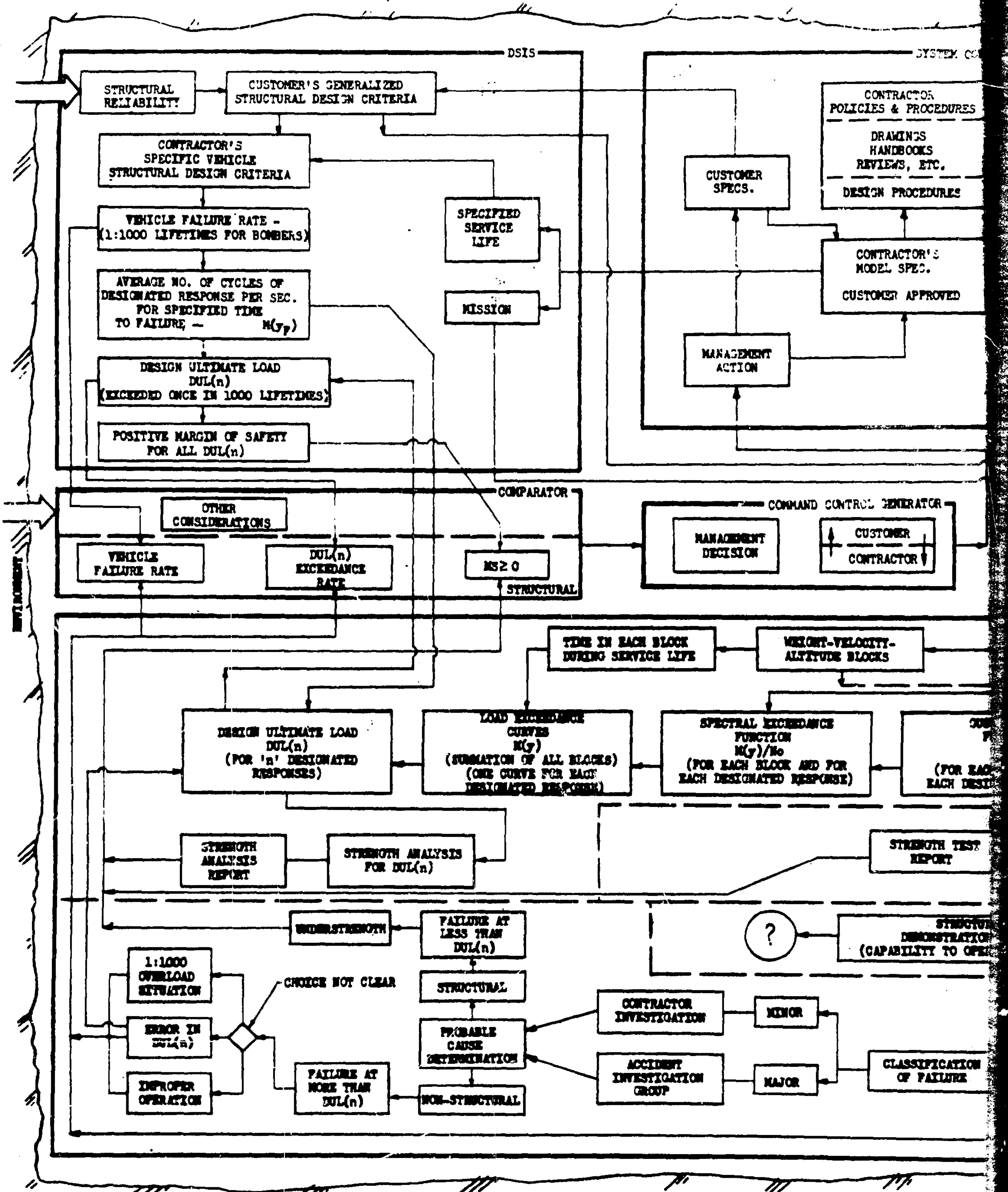
A report by Austin, Reference 29, presents a new procedure for the structural design of vehicles subject to low-level turbulence. This approach to the problem is a unique combination of the two basic systems described and evaluated in Sections II and III. As such, there are some special considerations involved in critiquing this procedure. Since the procedure cannot be discussed in terms of the functional diagrams of Section II, a new diagram for the system is presented as Figure 22. Presentation in this form will help in clarifying the advantages and disadvantages of Austin's approach.

In the analysis that follows, it is shown that the approach represents a necessary step in defining the environment if a quantitative structural design criteria by statistical methods is to be developed. However, it is also shown that only a part of the problem has been considered. Therefore, the structure designed according to the procedure of Reference 29 may or may not meet the criterion set forth by Austin. This criterion is that "Loss of one aircraft due to structural overload shall be expected in 1,000 aircraft lifetimes." Furthermore, the procedure by itself has no provision for verifying or proving that the structural system does satisfy the criterion. These statements are amplified in the following discussion.

Many of the problem areas noted in Sections II and III and under the evaluation of the previous papers are applicable to Austin's approach. However, one of the major problems has been eliminated by the procedure of defining an ultimate design load. This converts the reliability requirement into a deterministic number. Proof of compliance that the structure has the requisite strength for this ultimate design load is the same as in the Present System. The strength is initially proved by submittal of a strength analysis report. The final proof of compliance is successful completion of a strength test load corresponding to the ultimate design load.

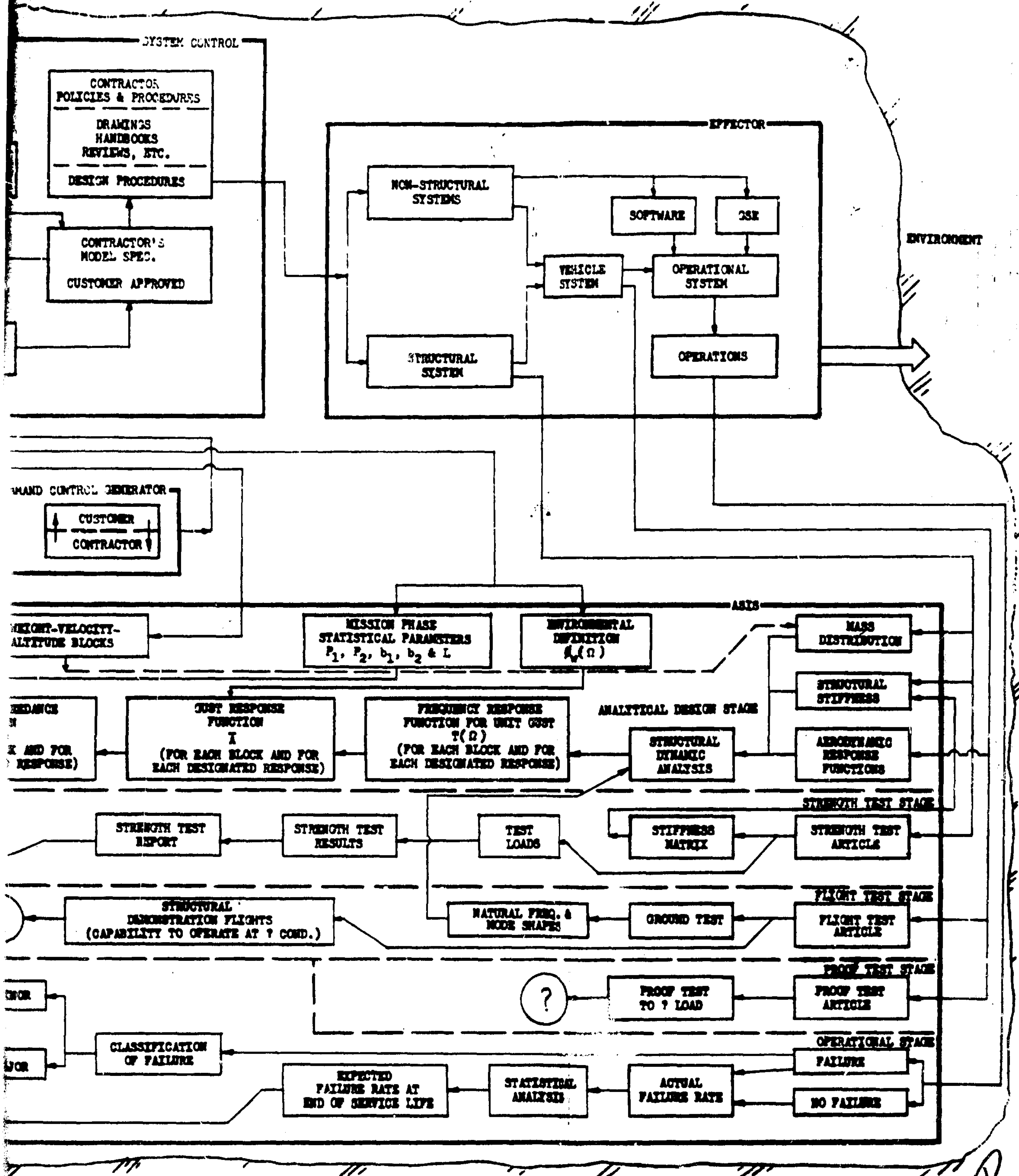
The difficulty in this approach is that there is no demonstrable correlation between the proof that the structure can support the designated ultimate design load and the actual failure rate due to structural overload. Assumption of this correlation is the basic premise of the approach. It is shown on Figure 22 that there is an inherent assumption that the time to failure, T_F, of the structural system will equal or exceed the desired value if a Design Ultimate Load (DUL) can be established such that the time to exceed the DUL is equal to or greater than T_F, and if the strength of the structure (as demonstrated by a strength test) is greater than the DUL. This relationship is shown dotted on Figure 22 because it can be shown that fulfillment of the two secondary objectives does not necessarily mean satisfaction of the primary objective.

It is presumed that the meaning of the requirement that the strength should exceed the DUL is as it is in the Present System. If so, the strength is proved first by an analysis showing a positive margin of safety and then



AUSTIN'S

FIGURE



AUSTIN'S SYSTEM

FIGURE 22

by a strength test. Even if the load exceedance curve is precisely as calculated and the DUL is precisely that load that occurs once in 1,000 aircraft lifetimes as prescribed, the probability of failure will not in general correspond to the designated value. This is shown in Figure 23 where curve (1) is computed (using the structural reliability program described in Volume III) on the basis that the probability of exceeding DUL is 0.001. It is assumed also that the 99-percent-exceed (the typical allowable) strength is matched exactly (zero M.S.) with the DUL. Curve (1) corresponds to the assumptions of Reference 29. Given these conditions it is shown that the probability of failure varies widely from the desired 0.001 value. Figure 23 identifies the significant effect that the coefficient of variation in strength has on the probability of failure. Thus, the implicit assumption on which this procedure is based is demonstrably in error. Additional discussion of Figure 23 is contained in the Appendix.

There are additional problems that must be considered before it can be accepted that this proposed procedure would result in structural systems that meet the stated objective. In the discussion of Reference 11 it is noted that the theoretical analysis of probability of failure is invalidated by errors in the calculation of the loads and strengths. This discussion particularly considers the question of errors in the strength analysis. It is noted that 10 years of static test experience at Wright-Patterson Air Force Base, as documented in Reference 17, show that sizable errors in analysis are not infrequent. The personal experience of any knowledgeable structural analyst should confirm the general trend of the Reference 17 data. The results of a computation of the probability of failure, considering that the error frequency is equivalent to that of Reference 17, are presented as curve (2) on Figure 23. This computation shows that, if the determination of the probability of failure is based on analysis alone, with the possibility of error included, the resulting value is far from the desired value as established by Reference 29. Curve (2) also shows that, if the accuracy of analysis is assumed to be ten times better or worse than the Reference 17 data indicate, the probability of failure remains at the same order of magnitude. Furthermore, an assumption of log-normal or Weibull distribution rather than normal affects the spread of curves (2) and (3) very little.

Curve (3) of Figure 23 indicates the increment in structural reliability resulting from the usual practice of rejection, during the strength test to the DUL, of most of the understrength systems. This curve shows that the probability of failure is almost certain to be different from the prescribed value, even though the DUL is precisely as desired and that the strength of the structure is developed through presently accepted analysis and testing procedures. The discrepancy would be further increased if the inevitable errors in the assumed load distributions were included.

Sections II and III discuss some of the problems of calculating the load spectrum accurately. Because of these difficulties it is most likely that the actual probabilities of failure are worse than the computed values presented on Figure 23 based on the assumption of no error in the loads analysis. Figure 22 illustrates the fact that the DUL is dependent on the specified values of the turbulence parameters and the frequency of encountering both normal and severe turbulence. It is also dependent on the dynamic

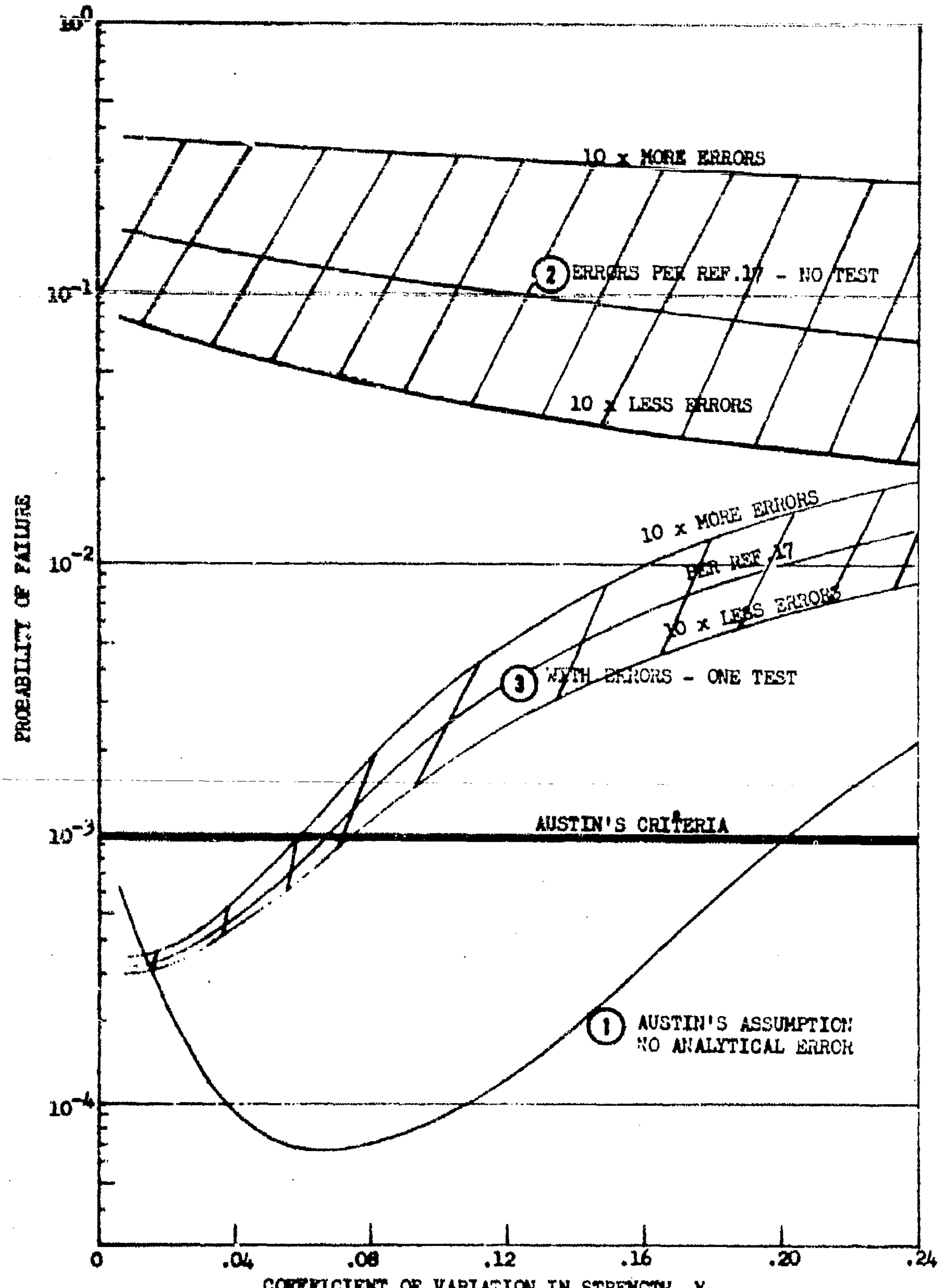


FIGURE 23 - PROBABILITY OF FAILURE VS. γ_s FOR AUSTIN'S CRITERIA

load response of the vehicle. None of these is subject to direct validation during the design and test stages of a new vehicle. The spectral exceedance function, $M(y)$, and the particular value $M(DUL)$ for the DUL, are subject to comparison only with the analytically determined values. There is no procedure suggested for verifying or proving compliance with this function even though it is of equal importance with the strength in determining the actual failure rate.

Finally, the desired failure rate of less than one in 1,000 lifetimes cannot be verified statistically. One failure at an early stage of fleet deployment does not prove that the average failure rate is greater than the established rate. It is conceivable that the failure was a random one and that there will be no further failures during the fleet life. Even if there are two or three failures, there is no absolute proof of non-compliance, although such a situation would obviously represent presumptive evidence.

The foregoing is the crux of the argument that Austin's procedure does not insure that operational vehicles will meet the prescribed failure rate. This is not to say that most of them won't be reliable enough. Most will be. This is not to say that the analytical procedure for determining the gust environment and vehicle response should not be vigorously pursued. What it does say is that, after following the procedure, the resulting vehicle may or may not have the desired failure rate. The same thing could be said of any other procedure no matter how unsophisticated. Therefore, the presumption that the procedure will always prevent the failures that have occurred in low-level operations cannot be substantiated. Neither can the implication that other procedures, such as the discrete gust procedure of MIL-A-8861, are unacceptable be sustained. The fact that this procedure is very logical for the problem it considers is no justification for deciding that it is the best procedure when all of the considerations that affect structural design are included in the formulation of the problem.

There are several additional questions that should be considered in evaluating this approach. These are secondary to the basic questions but they will affect any future application of this procedure. The first of these questions involves the technique associated with the power spectral approach. There is some question whether the basic assumptions involved in Rice's original paper[32] are applicable to the determination of the frequency of occurrence of extremely large, extremely rare gusts such as would be involved in the Design Ultimate Load. In some ways such large and rare gusts answer the description of a discrete gust which is the basis for the MIL-A-8861 requirements and most aircraft gust design to date. Rice's work and the adaptations of it cited by Austin in References 29, 30 and 31 are based on certain fundamental assumptions that may be violated when applied to the problem of extremely large gusts. The description of the gust environment by the power spectral technique probably is quite adequate and not a violation of the fundamental assumptions for the lower amplitude gusts that contribute largely to the fatigue problem on aircraft. It is assumed that the process is a stationary, random process. Further, it is assumed that the process also belongs to the subclass known as ergodic. Furthermore, the prediction of the frequency of exceedance function is dependent on the assumption of a normal or Gaussian distribution. There

is evidence that gust distribution is non-Gaussian. It is beyond the scope of this paper to delve deeply into the mathematical verities of the power spectral technique as applied to the definition of large magnitude gusts. However, qualified mathematicians should examine this question very thoroughly rather than uncritically adopting the technique as the design requirement.

The validity of the numbers obtained for design purposes is crucially dependent on the environment defining parameters such as set forth in Table 1 of Reference 29 and on the frequency response function, $T(\Omega)$, of the vehicle. Unless there is a practical technique for verifying these numbers or the exceedance rate of DUL, the Austin approach cannot be administered properly. There are two other detail problems that were not considered explicitly in the development of this procedure. The first is the possibility that the failing strength of the structure may be time dependent. There is an implicit assumption in the approach that no structure will ever fail at less than the DUL at any time during the 1,000 lifetimes and that all structures will fail if the DUL is exceeded. If the instantaneous strength at any time during the vehicle lifetime is higher or lower than the DUL, the failure rate will not be identical with the frequency of exceeding the DUL. Thus, the basic goal of Reference 29 might not be met even if the procedure given for the derivation of the design ultimate load is followed precisely.

The second detail problem involves the definition of the DUL for more than one parameter. Reference 29 does not discuss the situation explicitly but there is an implied consideration of more than one load at a time. The procedure speaks of Design Ultimate Loads in several places and the term "specified response" is used. Also, Reference 31 speaks of wing bending moment, fin shear and fin bending moment. Therefore, it can be assumed that there would be a DUL for every critical location throughout the vehicle. Failure at given location is not usually a function of a single parameter. There are interactions between the various loading conditions. It might be necessary to know the shear, bending moment and torque at one wing station together with the same parameters at inboard and outboard stations (to allow for shear lag effects, for one thing). In addition, it might be necessary to know the local pressure because of its effect on panel buckling. If a DUL for each of these parameters is calculated, the resulting combination may not represent the true failing situation at all. It is quite possible that the combination of the various Design Ultimate Loads might result in a physically incompatible situation. Determination of structural survival or failure requires the definition of a discrete set of physical loads that occur simultaneously.

The problems represented by the time-dependency question and multi-parameter failure modes are not inherent in the proposed procedure. These problems could be solved within the framework of Austin's philosophy although the details of how to accomplish the solution are not clear at the present time. A word of caution is pertinent at this point. Reference 29 (and others) have discussed functions such as $M(y)/N_o$ as though they represented the probability of exceeding a value of the parameter in question. For instance, on page 3 of Reference 30 it speaks of "the probability of equaling or exceeding the response parameter, y, can be

expressed" as $M(y)/N_o$. On page 3 of Reference 31 it says that "$M(y)/N_o$ is the probability of exceedance" of the true gust velocity. NASA data on the statistics of maneuvers[33] has been presented in a similar form.

It is not apparent to the uninitiated that this type of probability is a conditional probability. It represents the probability that, if a gust (or maneuver) is encountered, the value of that one gust will exceed the value y. This conditional probability can be envisioned as the fraction of the gusts exceeding a given value out of all the gusts being considered. Accordingly, the probability of the gust velocity, shown at the 10^{-6} level on Figure 2 of Reference 31, may actually approach 1.0 if there are 10^8 gusts involved. Likewise, the probability of exceeding the gust velocity shown at the 10^{-1} level may approach zero if the number of gusts approaches zero. Another way to explain the situation is to point out that $M(y)/N_o$ is the same whether one is considering one hour or a million hours of flight. On the other hand, the probability of exceeding a given gust velocity increases steadily as the time involved increases from one to a million hours. Experience has shown that the conditional probability form of the function is not as meaningful and significant to the average engineer as is the probability of exceedance during a specified period.

There are several interesting questions pertaining to the philosophy of structural design criteria and structural design systems that are raised by Reference 29. One is the precise meaning of structural reliability or Austin's variant, the total time to failure. In the discussion of Reference 11, it is pointed out that there are three orders of reliability. It appears that Reference 29 is concerned with a group or fleet of nominally identical vehicles of a particular design. The question needs to be clarified in establishing the objective of the procedure.

Another philosophical question that is pertinent to the evaluation of any procedure such as Reference 29 is the procedure for defining the mission for which the vehicle is to be designed. Coutinho,[34] along with many others, points out that "It is not possible to build a minimum weight airframe structure which will never fail." Elsewhere in his paper, Coutinho states that "The objective of these (reliability) procedures is to produce an airframe structure of minimum weight which will perform its mission without failure." Both of these statements imply that failure may be more acceptable during operations beyond the specified mission.

The specified or design mission for an aerospace vehicle is of extreme importance in the question of the structural integrity of an aerospace vehicle. Once the vehicle is designed and in operation, its structural integrity depends on insuring that the operations are no more severe than those of the specified mission. In Austin's procedure, there is an inherent assumption, used many times previously, that the future mission and the resulting operations will be the same as in the past. Obviously, this is not necessarily the case. Therefore, the failure rate that is established as the objective in Reference 29 must be qualified as the rate that will be obtained if the vehicles are all operated in accordance with the specified mission. It must be accepted that if non-specified missions are flown, the failure rate most likely will be different than the specified value.

This is not to say that alternate mission capability should not be incorporated as part of the specified mission. If flexibility in deployment is required, it must be designed into the vehicle. Particularly difficult to resolve is the question of whether operational vehicles should be designed for non-operational usage such as air-show demonstrations and research projects. It seems obvious that such requirements should not be allowed to increase the weight of a vehicle capable of satisfactorily fulfilling the normal military requirements. Nevertheless, it is difficult to resist the pressures to beef-up a vehicle that fails during such extra-curricular activities. Perhaps the solution is to specify what the vehicle is not intended to be good for as well as what it must be good for.

In any event, if the vehicle is to be designed for a specifically limited mission, there is a missing link in the development of structural reliability when there is no specified interface with non-structural systems including flight operations. To prevent structural failures there must be a control procedure to limit the structural environment to that for which it is capable of survival. This control procedure should include allocation of responsibility for specified actions and monitoring the results of such actions to provide timely warning of more severe operations than would be encountered while performing the specified mission.

Another problem is how to restrict the operations to the prescribed operational capabilities of the vehicle. Limit conditions are a very useful tool of communicating the operational limitations to the user. Absence of any determination of limit conditions may prove to be a critical omission in Austin's approach.

Another important aspect of the need to define the interfaces with other systems is illustrated by the discussion of the use of a yaw stability augmentation system (SAS) to reduce fin loads. Use of such a system to reduce the Design Ultimate Load (DUL) raises a very significant question for structural design criteria — whether or not statistical methods are involved. It is quite conceivable that the SAS could be so effective in reducing the DUL that the structure would be almost certain to fail if the SAS failed. There are many other instances known where the load environment of the structural system is dependent on the proper functioning of a non-structural system. There is no indication on Figure 8 of Reference 31 that any provision has been made for including the probability of failure of the SAS in the calculation of the load spectrum with stability augmentation. Even more important than such a calculation (which is subject to the possibility that the non-structural system will fail more often than assumed) is a question that must be decided somewhat arbitrarily. The question of who is responsible for preventing a structural failure due to failure in a non-structural system (including a SAS) is an executive decision. The decision can be that, if the non-structural system fails, the structural system is expected to tolerate and survive the resulting loads. On the other hand, the decision could be that the structure is not required to survive such a non-structural failure. In this case, the responsibility for preventing the failure rests with the non-structural system which must be so designed so that it will not fail any oftener than will be tolerated for structural failure. In other words, the responsibility for preventing the structural

failure is transferred to the non-structural system. This has many ramifications that need to be explored further.

Evaluation of Austin's procedure by the standards listed in Section 4.3 results in the following conclusions:

1. The procedure establishes very explicitly the Desired State of the structural system. The Desired State is that there should not be more than one aircraft loss due to structural overload in 1,000 aircraft lifetimes.

2. The procedures makes no direct provision for accurately determining the actual failure rate for comparison with the desired value. It is assumed that calculation of a Design Ultimate Load which has a frequency of exceedance of one in a thousand will result in an operational system which will have a structural failure rate less than one in a thousand. There are many reasons why such an assumption cannot be justified. For one, Figure 23 shows that the probability of failure can vary from 0.37 to 0.000068 depending on many parameters other than the probability of exceeding Design Ultimate Load.

3. The procedure makes no explicit provision for disclosing discrepancies between the Desired State and Actual State. There is an implied assumption that the structure will be strength-tested to the Design Ultimate Load. Curve 3 of Figure 23 shows that the probability of failure after completion of the typical strength test can vary from 0.021 to 0.00029, depending on the coefficient of variation in strength (and to a small degree on the type of strength and load distribution). This difficulty in determining the true probability of failure when the load distribution is assumed to be known is compounded when possible errors in load distribution are introduced. As a consequence, there is no rational and accurate mechanism for determining whether the vehicle structural system actually satisfies the specified objective of the procedure.

Austin's development of a rational probability analysis technique for defining the Design Ultimate Load for aircraft is a significant contribution to the state of the art. In particular, an inherently logical approach of establishing a quantitative objective is followed. A procedure intended to satisfy this quantitative objective is developed. All the discussion in this evaluation of Austin's approach is concerned with the detail problems of implementing the objective. It is suggested that the proposed technique should be considered as a good beginning to the solution of an important technical problem. This first step should be followed up by expanding the approach to include more of the pertinent considerations involved in defining the true structural reliability.

(5) Taylor

A book by Taylor, Reference 35, is a reference work concerning the loads experienced by aircraft plus a chapter on design philosophy. The book's chapters on loads are an excellent compendium of all the phenomena that induce loads on aircraft. Much of Taylor's data is presented in the statistical format that is necessary for a structural reliability approach. In short, there is a wealth of pertinent statistical information presented in a convenient package. However, as in any manual or handbook of this type, there can never be enough information presented between the covers of a book to serve as the sole source for the design of a modern, sophisticated aerospace vehicle. It can only be a good start.

Chapter 13, titled Design Philosophy, is a convenient presentation of what Taylor considers should be incorporated in a rational design procedure. All of the elements involved in the structural reliability approach are discussed, some more extensively than others. The basic philosophy of Reference 35 can be characterised as the Purely Statistical Structural Reliability System evaluated in Sections II and III. Many of the problem areas noted in these discussions and under the evaluation of Reference 11 are applicable to Taylor's approach. However, Taylor shows more awareness of the problems than most authors in the field of structural reliability even though he doesn't present solutions.

Page 282 of Reference 35 defines the essence of the approach followed. It states that "The refinement that is introduced by this procedure is that the applied loads and design strengths are, after manipulation, related by one single numerical value. This is a direct measure of reliability; however it has been obtained from formulae for frequencies of occurrence of loads and strengths that are extrapolated far beyond practical experience. Thus the engineering judgement that was used to estimate the factor between applied load and design strength is transferred to estimating the appropriate formulae for extrapolation."

Reference 35 starts the discourse on Design Philosophy by noting that "The purpose of all philosophies of structural design is to produce reliability and reliability may be defined as the certainty with which the structure should withstand the loads that may be applied to it." On page 286 it is stated that "...it cannot be emphasized too strongly that the object of structural design is to obtain a design that is reliable."

One aspect of the structural design problem that is not included in the objective is consideration of structural weight along with reliability. Anyone can design an extremely reliable structure if weight is of no concern. However, Christenson[36] points out that "Design for safety does not mean pure brute strength without regard for economic feasibility." Nothing would destroy the economic feasibility of an airline aircraft more quickly than a grossly overweight structural system. Coutinho[34] recognizes minimum weight as a structural objective when he says "The objective of these procedures is to produce an airframe structure of minimum weight which will perform its mission without failure. Achievement of minimum weight is a competitive

consideration, whereas structural safety involves safety of life and is an absolute necessity." Bouton[3] stated the problem in slightly different form — "The question to be answered is: How weak can we design our structures without incurring the risk of 'too many' failures?"

Another facet of the statement of objective in Reference 35 that should be considered very carefully is the pronouncement that "the structure should withstand the loads that may be applied to it." This should not be an unqualified statement. It should not be the intention that the structure should survive any conceivable gross overload including situations precipitated by failure of non-structural systems nor should it be the intention that the structure should tolerate any conceivable gross error in the design, fabrication and maintenance of the structure. It should be the responsibility of the structural system to survive only a limited range of definable operational situations. Responsibility for avoidance of failure beyond these defined situations must be assigned to and accepted by systems other than the structural system. The structural design system should identify and define these interfaces with non-structural systems.

Reference 35 establishes "the reciprocal of the combined frequency that the load is greater than the strength" as the numerical value for reliability. It also states that the dimension of reliability "must inevitably be number of hours per failure." However, it does not make clear how a particular value of reliability will be established as a requirement for a particular vehicle system. Furthermore, on page 286 the absolute value of reliability is judged to be "most inaccurate." Despite this appraisal, it is stated without qualification on page 300 that "The reliability of the structure under static loads is calculated using the following three parameters...." On page 301 it is stated that "The probability of failure is given by... Equation 13.1." This equation forms the basis for the subsequent analyses.

The nature of the Desired State definition in the procedure is illustrated by the suggestion on page 287. It is proposed that the overall reliability of a structure (measured in hours to failure) be multiplied by factor of 10. This arbitrary value is based on the assumption that the weakest part will contribute at least 10 percent to the total chance of structural failure. If the absolute value is most inaccurate and the relationship between part reliability and total reliability is not really known, it is difficult to comprehend what will be gained by establishing an absolute reliability requirement for a particular design.

One other concept in the definition of the Desired State is the assumption on page 325 that it is common practice to allow margins for error and for ignorance. This is a common assumption that should be challenged. Curve 2 in Figure 23 in the critique of Reference 29 shows that, if the ignorance and error represented by the design practices revealed by the Wright Field test data of Reference 17 is any criterion, approximately one out of every ten vehicles would fail even when the common 1.5 factor of safety is incorporated in the design. That is, one out of ten would fail if the errors were permitted to remain in the operational vehicles by omitting the static test. If the errors are disclosed by a testing operation and the design corrected to eliminate these errors, then the reliability increases

to the desired value — provided the coefficient of strength variation, V_s, is of the order of the typical aerospace structure of the past (Reference 35 states that the value is less than 0.043) and provided that the loads errors are eliminated by flight test measurements. Scatter in strength and load is not synonymous with error but is a fact of life that must be considered in the determination of the structural design. If the mean is calculated or predicted to be at one value and if, in truth, it is at a value only half as large, then this discrepancy is an error.

Another element of the Desired State that is not considered is the probability of failure at limit load or less. Sections II and III note that a zero failure rate is desired at limit conditions or less. This requirement is established by the fact that limit conditions, by definition, are permissible and, thus, expected to be safe. A situation such as illustrated by Case E on Taylor's Figure 13.3 should not be considered as acceptable even if the total failure rate is acceptable. The illustration shows about 30 to 40 percent of the failures occur below the 2.64 G value designated as the expected or limit condition. Reference 5 proposes that a limit reliability objective be established corresponding to no more than one percent of the total number of failures that would be tolerated.

One final comment should be made on the Desired State for structural reliability during landings as illustrated in the example in Reference 35. A failure rate of one-in-ten-million landings is selected as a goal (or Desired State). It is indicated that the example aircraft are expected to achieve 10,000 landings per lifetime. On this basis one landing failure in every thousand aircraft is established as the goal. Since more than 10,000 DC-3/C-47 type aircraft were put in service, this would mean that application of the procedure would deliberately set a design goal that would result in about 10 landing failures for this type aircraft. This is the result that would be attained if the design were exactly as predicated by the analysis of pages 308 to 311. It could be worse if any errors are made in the analysis. It is questionable whether such a goal would be acceptable in the design of commercial transport aircraft.

The determination of the Actual State of the structural reliability of a given structural system depends almost exclusively in the procedure of Reference 35 on the evaluation of Equation 13.1 on page 301. An initial formulation of the load and strength distribution is given in Equations 13.2 and 13.3. Subsequently, other distributions are introduced for consideration.

Before presenting Equation 13.1, Taylor makes a cogent observation that should be considered by all those who are developing structural reliability procedures. "Throughout the analysis the probability of failure will be determined as the sum of the probability of failure at each strength. Mathematically this is identical to the sum of the probability of failure at each applied load, but physically it is more realistic to think in terms of structures that broke because the load surpassed their strength than in terms of loads that caused failure."

Reference 35 presents several distributions of strength including normal, exponential and bimodal. The bimodal distribution is described in terms of

a main family and weak family. The phenomenon of a weak family in a strength distribution appears to be more common than most other authors assume. The bimodal distribution generally has a major effect on the calculation of structural reliability. As Taylor put it, "Attention has already been drawn to the added complication that the exceptionally high loads and the exceptionally low strengths may well be from families that are subsidiary to the two main ones. The contribution from the subsidiary families to the calculated probability of failure will be a large proportion of the total, which will consequently be subject to considerable error."

The load distributions in Reference 35 are representative of the data that is generally available. As with the strength distributions, it is pointed out that many loading distributions are bimodal. It is explained that there is "a strong possibility that the measurements will be only from the main family. Thus, a subsidiary family will need to be postulated for the severe conditions, basing it on evidence from other types of loading conditions in which the extreme conditions have been experienced." The accuracy of extrapolations based on very limited quantities of data is exemplified in the illustrative problem. On Figure 13.13 the load distribution function is extrapolated to 10^{-7} and beyond. The curve is based on records of 320 landings documented on Figure 13.8C. As noted on page 109, Reference 35 acknowledges that a factor of ten should be applied to the number of data points to define a probability with even 90 percent confidence. This means that the loading data is valid only to one in 32 or 0.03 (five orders of magnitude lower than the region of most interest). The difficulty is spotlighted still more by the use of a normal distribution and an exponential distribution with their obviously large difference in the region with the most impact on the final results of the reliability calculation.

Figure 13.13 and the attendant discussion can be used as the perfect illustration of the problem of administering a Purely Statistical Structural Reliability System. It can be assumed that various analysts confronted with a real design problem might arrive at a range of designs comparable to the five solutions presented on Figure 13.13. Who can doubt that the competitive considerations Coutinho[34] speaks of might lead some contractors to the lightest weight design shown as Condition A. On the other hand an engineer at the procuring agency might decide Condition E was more realistic. This would require a mean strength about 46 percent higher than required for Condition A. The corresponding weights would undoubtedly be close to the same proportions. Reference 35 in posing the problem gives no hint of how the choice could be made objectively. It is postulated in this critique that such problems are deterrents to a universal acceptance of structural reliability as the basis for structural design criteria.

Evaluation of Taylor's procedure by the standards listed in Section 4.3 results in the following conclusions:

1. The approach is based on the achievement of structural reliability which is defined "as the certainty with which the structure should withstand the loads that may be applied to it." It is indicated that there would be a prescribed standard of reliability. In an example case a failure rate of one in 10^7 landings is chosen. While Reference 35 is

not too explicit on how the Desired State value of structural reliability would be chosen, it is clear that such a number would represent the Desired State in the proposal.

2. The problem of determining the Actual State of the reliability of a structural system is not solved by the proposed procedure. The procedure presents the same difficulty as most of the other approaches in that it depends exclusively on the computed structural reliability and does not recognize the possibility of errors in the computations.

3. A numerical example of the procedure applied to the solution of a landing reliability problem is presented. Five cases with various assumptions for the load and strength distributions are discussed. All have the same calculated structural reliability yet the range of strength is such that the mean strength of the strongest is about 46 percent greater than that of the weakest. Any one of the five designs would apparently satisfy the requirements yet no procedure is presented for deciding which one to choose initially. Also, if one designer chose the weakest design and another designer the strongest, no procedure is proposed for disclosing which system meets the prescribed failure rate and which does not.

(6) Lundberg

A paper by Lundberg, Reference 13, presents the gist of the extensive work by Lundberg and his colleagues in the field of structural design criteria by a quantitative statistical approach. Much attention is concentrated on the fatigue aspects of the structural reliability problem. Other presentations of the approach are given in References 37 to 39.

Many of the problem areas described in the discussions in Sections II and III and those considered in the evaluation of Kluger's paper are applicable to Lundberg's approach. In the Reference 13 approach there is no procedure for accurately measuring the actual structural reliability of a particular structural design. As a result, there is no proof of compliance technique available to verify the analysis and demonstrate that a contractual requirement has been fulfilled.

Two assumptions that are made in Reference 13 bear on the difficulty of analytically predicting the structural reliability of a new design. Lundberg's approach, called the "Allotment of Probability Shares," or APS, is based on an inherent assumption that the probability of failure of each part in an aircraft structure is independent of every other part. The probability that is to be allocated is the probability of failure per aircraft hour. This probability is derived from such considerations as an estimate of the number of individual accidents that will be tolerable, the numbers of passengers per aircraft, the average aircraft speed and the passenger-miles per year.

The hazards of predicting the future on the basis of past experience tempered by some form of judgement are clearly indicated in the curves

presented in Reference 13. Figure 3 shows the expected growth in passenger-miles per year for civil aviation. The predicted value for the year 2000 is 1.5×10^{12}. This prediction represents a 50 percent increase over the value predicted five years earlier on Figure 1 of Reference 39. Figure 6 of Reference 13 (published in 1962) predicts an average aircraft speed of less than 300 mph and average passengers per aircraft of less than 50 for the year 1967. This should be compared to the 500-600 mph jets currently in service carrying as many as 200 passengers. The speed projected for the year 2000 is 400 mph which will certainly fall far short of the speed of the projected SST's. Likewise, the year 2000 figure of 60 passengers per aircraft will be far short of the 500 or more expected for the "jumbo jets" currently under development. The use of such figures as the basis for formulating the desired reliability could certainly be questioned. The problem is clearly recognized in Reference 39 where it is stated that "'past experience' — so often referred to in airworthiness discussions — is in fact of minor significance or guidance, at least in statistical analyses and predictions." It goes on to say "the fact that a design 'has proven to be satisfactory' during even a considerable service life is by itself not a sufficient proof that it will represent a satisfactory safety standard for the future."

Predictions of the type just discussed have one advantage over most of the elements in a typical structural reliability analysis. The figures can be verified periodically. This provides a sound basis for updating the prediction. The discipline of being subjected to eventual verification can be expected to result in better analytical procedures for such predictions. Many of the structural reliability analyses are not subject to this same discipline.

The "Allocation of Probability Shares" or APS is presented in Reference 13 as a statistical approach to the safety problem. The APS Method starts with the proposal that a total accident rate of no more than one in two million flight hours is the goal. The number was chosen as just described on the basis of the expected operational statistics for 1980 and beyond. Besides the problems inherent in extrapolating past experience to prediction of the future, the derivation of the reliability goal is based on the questionable assumption that the failure rate is linearly related to the hours of flight operation. There is considerable evidence to the contrary. Many of the structural failures in the past have been the result of an unknown design deficiency that existed at the time of the introduction of a new design into service. Subsequent events disclosed the error which was corrected after which that type of failure never recurred during the life of the particular vehicle. References 22 and 40 document a number of such problems. After describing the initial problems and their solutions for two well-known transports, Serling says in Reference 22 that they "since have earned a fine reputation for dependability and safety." Speaking of a third design that experienced fatigue failures, Serling says that today the airplane is "rated by pilots as one of the best short-range transports ever built." In describing the troubles of still another design, Serling identifies the reason for most of the initial troubles. He states: "The only honest answer to its trouble is that it was tested adequately based on past experience, but that it was not tested sufficiently in areas where there had been no previous experience."

It appears that the statistical model for failures would be more rational if it postulated a major failure probability at the introduction of each new design and a minor increment associated with flight hours accumulated after the initial problems are resolved.

After establishing the goal for the total failure rate, the APS Method allocates portions of this total to various accident causes. In the proposed procedure about three percent of the total is allocated to structural failures. Of that amount about ten percent, or 0.3 percent of the total, is allocated to fatigue failures. The subdivision is carried further by allocating subshares to "safe-life" and "fail-safe" structural components and to various major components such as wing, fuselage, control system and empennage. Finally, the subdivision is extended to individual parts in each component. This allocation of failure rates is shown on Figure 9 of Reference 39. Figure 11 of Reference 13 shows a "probability cake" divided into pieces allocated to each individual part.

The rationale of the APS Method is that the probability of failure of each part is statistically independent of all other parts. This assumption is formalized in Equation (1) of Reference 38 as $P_R = \Sigma P_\nu$. The concept is carried out on Figure 9 of Reference 39 where it is shown that each of "n" parts is allocated the fractional portion of 1/n of the total failure rate.

The concept that the probability of failure is the summation of the individual probabilities is very common in structural reliability analyses. The assumption is not a tenable one in most structural situations. The parts are not independent in their failure mode. Almost all external loads imposed on a structural system result in internal loads on all of the components. As a result, the probability of failure of each component must be considered a conditional probability. The conditional probability is expressed as the probability of failure of the part given that all the other parts have survived. A simple example that makes the conditional reliability assumption plausible can be presented. Con ider a chain subject to the random loading distribution shown on Figure 24. If the links in the chain have a zero coefficient of variation in strength, every link will fail at the same load. Thus, if the links are designed for a load corresponding to 150 on Figure 24, the probability of failure of the chain is 10^{-3} no matter how many links in the chain. If more than one link is considered, the increment due to each additional link is zero. The probability of failure of all links is zero below a load of 150. The first link has a 10^{-3} probability of failure, all at 150. But the second link has a zero probability of failure at a load beyond 150 because the first link has zero probability of surviving beyond 150. The same is true for any number of additional links.

By the assumption of Lundberg and others, a 10,000 link chain would require that each link have a probability of failure of $10^{-3}/n$ or 10^{-7}. From Figure 24 this would require that each link be designed for a 184 percent load. In such a case, no links would fail at 150 percent or until the load reached 184 percent. Since the probability of this load is 10^{-7}, the probability of failure of the 10,000 link chain would be 10^{-7} instead

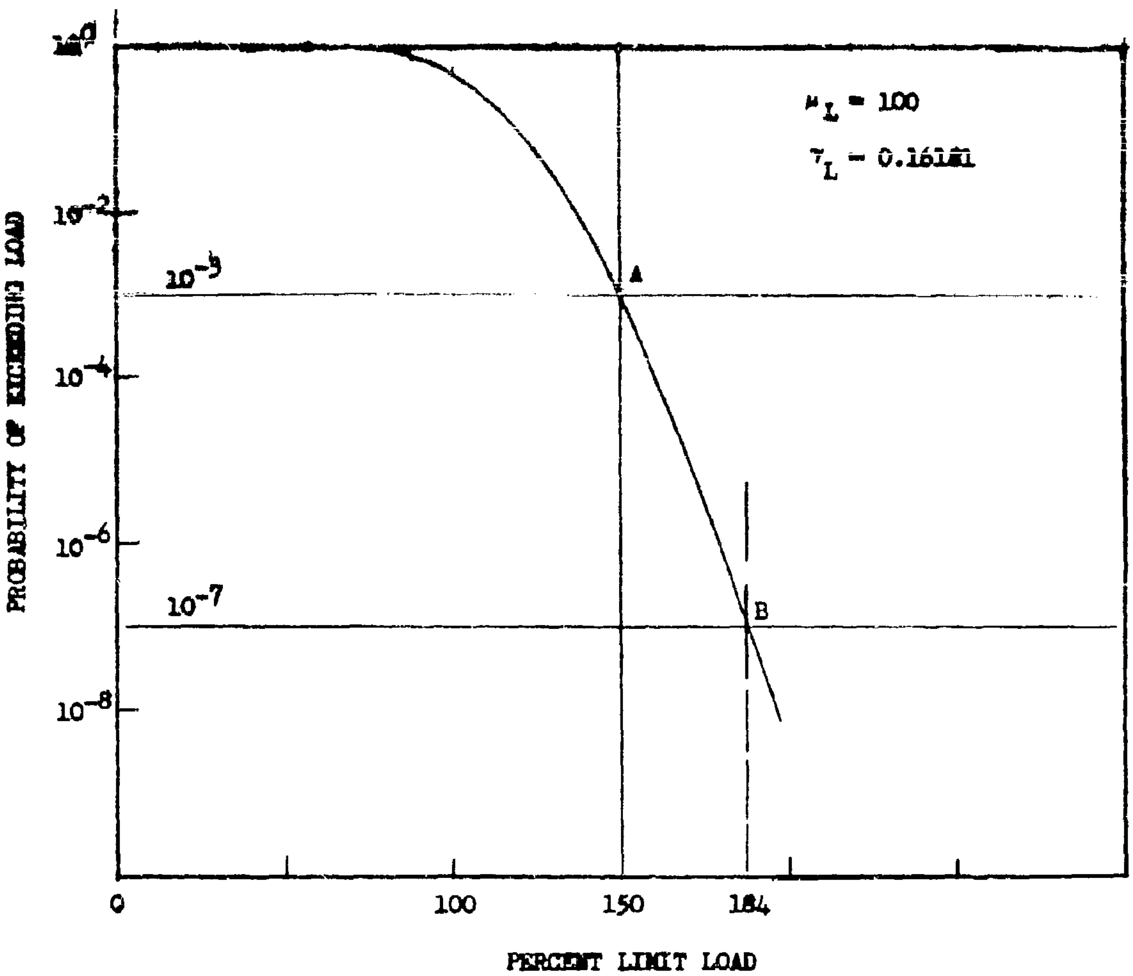


FIGURE 24

TYPICAL CURVE FOR LOAD PROBABILITIES

of the expected 10^{-3}. Figure 9 of Reference 3 shows that the proportional increase in probability of failure with number of components is the exception rather than the rule.

These two rather questionable assumptions on two major problem areas, taken with the impossibility of measuring the actual structural reliability (which, if available, would in itself be self-correcting for the other two problems), lead to the general conclusion that Lundberg's APS Method must be considered to be impractical for the design of aerospace vehicles.

Evaluation of Lundberg's procedure by the standards listed in Section 4.3 results in the following conclusions:

1. The approach defines the Desired State as a total accident rate of less than one in two million flight hours. This value is not unreasonable for the commercial transports considered. However, the particular value was derived from extrapolations of past trends that are questionable to the point where use of the rate proposed may not be acceptable in the foreseeable future. The allocation of this basic failure rate to individual parts in inverse ratio to the number of parts cannot be justified statistically.

2. The procedure encounters the same difficulty as other comparable methods in determining the Actual State of the structural system.

3. As a result of the lack of provision for measuring the Actual State, the procedure will be incapable of any early disclosure of possible discrepancies between the Desired State and the Actual State.

(7) Freudenthal

In Reference 15 Freudenthal presents the results of applying a theory of reliability estimation developed in References 41 and 42. Since Reference 15 summarizes the approach, the critique will be based principally on it with occasional mention of the other papers. The analysis of ultimate strength and fatigue strength are presented separately, so they will be evaluated in the same way. However, it should be noted that there is really no sharp line of demarcation between the two modes of failure. Reference 42 points out that "while the first mode is usually referred to as 'ultimate load failure' and the second as 'fatigue failure,' the latter is in essence, also an ultimate load failure but one involving a fatigue-damaged structure...."

(a) Ultimate Load Failure

The procedures for ultimate load failure as described in Freudenthal's papers are basically comparable to those proposed in Reference 11. A detailed examination of these papers shows essentially the same points for consideration that were discussed in the evaluation of Reference 11. The five points noted on page [illegible]3 are applicable to Freudenthal's proposed procedure.

Although it is not stated ·licitly, there is an implicit assumption in Reference 15 that the streng and load distributions are "known," presumably as a result of anal· al calculations. Sections II and III document the fact that these d ·ributions are not known after an analysis to the accuracy required to d· ermine structural reliability.

It is a well-known scientific principle that verification of a hypothesis is a vital element in the scientific approach. Figures 18 to 21 document the problem in the framework of Professor Draper's technique. The figures show that in a Purely Statistical Structural Reliability System the only measure of the Actual State of the Structural reliability of a vehicle system is in the analytical design stage. This is demonstrably inadequate for the determination or measurement of the Actual State. Therefore, any structural reliability procedure that depends on analysis alone must be considered to be an unacceptable solution to the problem.

Reference 15 takes up the question of the statistical definition of flight loads. In Sections 2 and 4 and on Tables 1, 2 and 4 of Reference 15 specific recommendations for the calculation of loads distributions used in the reliability calculations are presented. It is a virtual certainty that, if this procedure for calculating load spectra is followed by other analysts, the resulting loads spectra will not <u>always</u> be sufficiently accurate to result in vehicle designs that will <u>always</u> have the desired structural reliability. Sections II and III discuss some of the problems of calculating loads and loads spectra.

As a specific example of how different analysts will arrive at different answers to the same problem, consider the differences between the determination in Reference 15 and that in Reference 29 of the probability of exceeding a given gust velocity. Reference 15 presents some analytical results in Figure 1. There is no mention of low-level turbulence or of the effects of climb, cruise and descent. However, Reference 29 finds that each of these parameters has a significant influence on the gust velocity spectrum. Figure 5 of Reference 30 shows a gust velocity exceedance curve that is substantially different from that in Reference 15. It is interesting to note that neither author mentions a problem that is currently of major concern in the design of high-speed, high-flying aircraft: CAT, or clear air turbulence.

The point of all this is that different analysts will arrive at different solutions to the same problem. The same analyst may arrive at different answers before the vehicle is designed than he will after it is in operation and he has the benefit of hindsight. Therefore, it must be accepted that the analytically-determined load spectrum, on which hangs much of the validity of the structural reliability calculation, is not a known spectrum. A major problem in the definition of structural design criteria is how to make deterministic decisions affecting the structural design in the face of such uncertainty.

Another difference between the approaches is in their treatment of the dynamic response problem. Reference 15 does not consider it and Reference 29 finds it vital to the procedure. In effect, the response considered in

Reference 15 is the force, nW, applied to the total vehicle. Along with this definition of vehicle response is the implicit assumption that the vehicle failure can be defined in the simple terms of nW. It appears that this is an oversimplified assumption that would result in erroneous predictions of when failure occurs and, thus, of the probability of failure.

A simple but well-known example of how the response may play a major role in determining when failure occurs can be seen in a design with a store at the wing tip. The shear and torque may be very critical compared to the magnitude of the root bending moment. Also, the bending moments in the wing near the tip may be in the opposite direction from those near the root of the wing. It is dubious that the simple nW function could represent the failing conditions on such a wing.

Some of the detail assumptions made in the calculation of failure rates for the comparison on Table 5 of Reference 15 may be adequate for demonstration purposes but would be rather questionable in predicting the characteristics of future vehicles. A parametric study of the effect of the gust sensitivity factor, k_n, is presented on Figure 14. Since k_n increases with forward velocity, the curve would apparently show that the critical (down) probability of failure decreases with increased airspeed. This is contrary to the true situation. The probability shown on Figure 14 is based on the unspecified assumption that the strength is increasing along with the airspeed and k_n. For a down gust, the effect of the 1.0 g level flight load factor on the total load factor is such that the gust velocity corresponding to 1.5 times the larger limit nW will be larger. The probability of exceeding this larger gust velocity is less which is the basis for the unexpected decrease in probability of failure as airspeed increases.

After the parametric study is made using four values of k_n, one of the four is selected to determine the failure rate shown on Table 5. The estimated 14 gusts per mile is a constant whereas Reference 29 formulates the number of responses per second, N_o, as a function of the dynamic response among other things. In fact, Reference 31 notes that N_o will increase with the addition of a stability augmenter. Reference 15 then assumes an average cruising speed of 200 miles per hour to determine the average number of gusts per hour. There is no indication of how this average velocity for all aircraft operating over a 15-year period is determined or how it would be estimated for a new design.

It is almost axiomatic that no load spectrum analysis by itself can support a structural reliability calculation as necessary to insure very high reliabilities. The discussion of the formulation of the loading distribution indicated the analysis was no exception to the rule. Unless there is some procedure for validating the spectra predicted by analytical means, the structural reliability calculation will be just an exercise. The ultimate strength distribution is formulated in sections 3 and 4 and Table 4 of Reference 15. The same statements made relative to the accuracy of the load distributions are applicable to the strength distribution. Sections II and III discuss some of these problems. The discrepancy between calculated strengths and actual strengths as documented

in Reference 17 is the major problem. Some detail problems relative to the strength distribution calculations recommended in Reference 15 are considered in the discussion following.

The generalized probability distribution for the strength chosen by Freudenthal is a "t" distribution of three degrees of freedom. There is nothing wrong with such a choice over the central range of the data, but Reference 15 considers it to be unacceptable for extrapolation below 80 percent of the mean value. As a result, a log-normal distribution is introduced below the 80 percent value. The resulting formulation as equation 3.6 is neither more nor less justifiable in the region near the mean than other distributions such as normal, log-normal or Weibull. A fundamental question raised by such manipulations is the arbitrary manner in which the choice is made. It renders very questionable the probabilities of failure presented in Reference 15 on Figures 9 through 18 which range from 10^{-4} to 10^{-12}. This is not a problem in this formulation alone; it is common to any reliability analysis of this type. After all, it is hard to justify mathematically a 10^{-12} prediction based on the 170 data points represented on Figure 7. Taylor (quoting Lusser) on page 286 of Reference 35 has pointed out that a rule of thumb for "the number of specimens required to estimate the chance of failure is ten times the reciprocal of the chance." This would require a minimum of 10^5 data points and possibly as many as 10^{13} data points to substantiate the curves of Figures 9 through 18.

A more meaningful objection to the suggested strength distribution is in the normalizing process used to arrive at Figure 7 and Equation 3.6. The result of this manipulation is that there is built into the analysis an implicit assumption that all structures have the same coefficient of variation in strengths (γ_s), namely 0.05638. Table 3 shows a range of sample coefficients from 0.0149 to 0.0994, just for the limited amount of data Freudenthal reviewed. It can be shown that, if the hypothesis were true, it would be very unlikely (something of the order of a probability of 10^{-6}) that the distribution shown on Table 3 would result. Future designs are expected to involve brittle materials, large shells failing in buckling and material operating near the upper limit of its temperature capability which are known to have coefficients of variation up to 0.25 or 0.30. This assumption of an average γ_s eliminates any consideration of the powerful effect this function has on the true reliability as shown in the discussion accompanying Figure 23 and previously in References 4 and 5.

The stated reason for truncating the "t" distribution at 80 percent of the mean value should be examined carefully because of its significance in establishing structural design criteria. On page 15 of Reference 15 it is stated that the "t" distribution can be truncated at the 80 percent value "on the quite justifiable assumption that structures of lower strength will be eliminated by inspection during manufacture." It is indisputable that this is a goal of inspection but, unfortunately, the facts of the situation are different. Many cases of failure at less than limit conditions can be documented for both aircraft and space vehicles. These understrength situations stem from two causes. First, the basic design may be in error so that a structure fabricated in exact accordance with the drawings and specifications may fail prematurely. The failure of the Mariner 3 shroud

is typical of a number of failures associated with a design error.[47] Perfect inspection could not change this situation. Second, inspection procedures do not always reject structures fabricated outside the tolerances called for on the drawings and specifications. During World War II a troop-carrying glider failed catastrophically because a critical dimension on a wing strut fitting was less than 20 percent of the specified dimension on the drawing of the part. It has been reported that the engine support truss on an early space vehicle failed because the wall thickness of one of the tubes was about one-half the designated size. Inspection could have detected and prevented these two failures but for some reason they were accepted for operation. These are just three of the many instances of premature failure, spanning the period from simple aircraft to complex space vehicles, that could be documented.

The fact that failures occasionally occur due to understrength situations does not mean that such failures are as acceptable as failures due to operating beyond the specified limit conditions. In Reference 3 it is suggested that a goal of structural design criteria should be to have no more than one percent of the total number of failures occurring at limit conditions or less. This would furnish the basis for quantifying requirements associated with limit conditions which is not available in the formulation of the problem in Reference 15.

In the formulation of the reliability calculation on Table 4 of Reference 15, the mean value of the strength is assumed to be (1) at a load corresponding to the ultimate load ($P = 0.5$) or (2) at a load corresponding to 1.056 times the ultimate load ($P = 0.1$) since the reciprocal of $\alpha_{R,p} = 0.947$ is 1.056. The justification for the $P = 0.1$ assumption is discussed on page 26. It refers to data showing that 10 percent of the specimens give values below the specification minimum. These data are contained in Reference 46. The data in question appear to be for civil engineering materials such as mild steel and concrete. On the other hand, the "A" allowables which correspond to the specification values are intended to be 99-percent-exceed values. All indications are that the material furnished by the mills and accepted by the inspection departments of major contractors is substantially better than the minimum specification value for more than 99 percent of the specimens. The justification for the $P = 0.5$ assumption is the fact that there is normally only one strength test to destruction. However, Reference 17 shows that 43 percent of the wings, 50 percent of the fuselages, 82 percent of the horizontal stabilizers, 86 percent of the vertical stabilizers and 78 percent of the landing gears supported the ultimate load without failure on the first test. Modification resulting from the test failures resulted in all of the structures possessing at least the design strength with many having more strength than required. It appears that the average structure is 5 to 10 percent above the required strength value after successful completion of the tests.

It appears that, regardless of where the average structural strength ends up in practice, it is unwise to deliberately design the structure so that 50 percent of the structures will fail before the test load is reached.

When errors of the type documented in Reference 17 are added to the theoretical expectation, the number of test failures necessitating redesign would increase to the point where costs of redesign and schedule delays would be intolerable.

In the formulation of the equation for the probability of failure on Table 4 of Reference 15 and in the discussions of Section 4, there is an unstated assumption that failure of the airplane is defined by nW. This is incorrect in many instances. Some that relate to the local loads were discussed in the section on loads distribution. Others involve the fact that each component is designed to survive a number of critical loads. One of these will be critical and the component will have excess strength for all others. Furthermore, there is an inherent assumption that is often incorrect in assuming that the local component loads are linear beyond the limit conditions. At best, the choice of nW as the controlling function for failure can only give a crude approximation of the true situation.

The integration of the load and strength distribution to calculate a probability of failure is quite straightforward as given in Equation 4.7. However, as discussed in Sections II and III, the probability of failure calculated using the distributions assumed with no considerations of analytical errors may be several orders of magnitude better than the true value. Figure 23 in the Austin discussion presents some data on this problem, which is the major problem in actually predicting the probability of failure.

Table 5 of Reference 15 shows the comparison of failure rate between actual values and those predicted by the proposed method. The comparison is in terms of failure rate per hour. This implies that there is a direct correlation between hours flown and number of failures. Although such an assumption is made by many authors in the field of structural reliability, the assumption is unproven and it is open to serious question. In the discussion on page 103 the thesis is developed that the major failure probability is associated with the introduction of each new design. The increment associated with flight hours appears to be a minor portion of the total failure rate.

Data are presented in the form of probability of failure per gust in Figures 9 to 14 of Reference 15. As discussed under the Austin evaluation, it is not apparent that this is a conditional reliability. Consequently, these numbers require another number to make them meaningful. Accordingly, it is suggested that such data be presented in terms of probability per vehicle lifetime to enhance its usefulness in the design process.

The statement is made on page 43 of Reference 15 that "the majority of structural failures are at structural resistances near the mean." This question has been discussed before. It should be pointed out in this connection that the statement is critically dependent on the qualification attached to the statement. It is indicated that this assumes the (small) scatter in structural resistance presently achieved in production. The assumption is correct only if the scatter and the mean are as assumed. Sections II and III indicate that errors in analysis are frequent enough to invalidate this assumption. Furthermore, there is every indication that the

structures of the future may not be able to maintain the small scatter assumed. The increasing use of brittle materials, extremely high temperatures, and more critical buckling problems in very large shell structures all indicate that designers may be forced to use structures with large strength scatters. In such cases, the proportion of failures at values appreciably below the mean will increase.

On page 54 of Reference 43, the irrationality of the "belief that reliability figures of the order of 0.99, 0.999, or 0.9999 can be taken at their face value with respect to large structures" is pointed out. Unfortunately, structural design criteria and its implementation in a structural design system demands that yes-or-no decisions be made. If a structural reliability requirement is established as the criterion, there must be a procedure to serve as proof of compliance.

The approach to the problem of structural reliability against ultimate load failures, as presented in Reference 15 et al., is a major contribution to the development of the reliability concept as a useful tool of design. However, there are two major shortcomings in this approach. First, even though the reliability figures cannot be taken at face value, this is done when it is assumed that the load and strength probabilities are known. This assumption overlooks the possibility that there may be errors and discrepancies in the calculations. Second, the procedure allows no recognition of the need to disclose the potential errors with a certainty that is consistent with the desired reliability. As a result, there is no proof of compliance procedure that is a necessity if the proposed procedure is to fulfill the need for a practical procedure that can be incorporated into contractual requirements.

(b) Fatigue Failure

The analysis of structural reliability under fatigue conditions is presented in many reports such as References 15 and 41 through 44. The approach to the determination of the probability of failure in fatigue is an extension of the approach developed for ultimate failure. The same two shortcomings that are present in determining the load and strength distributions are present in the fatigue analysis. In addition, the problem of determining the strength distribution after any given time or number of applied loads adds additional opportunities for the actual strength distribution to depart from the calculated distribution. References 15 and 41 through 44 give no recognition of the need to disclose the potential errors with a high degree of certainty and no provision for a proof-of-compliance procedure. This is the basic problem from which stem all other problems affecting the calculation of fatigue reliability. Some of the detail problems are evaluated in the discussions following.

Reference 15 presents a discussion of fatigue reliability but it does not set forth a specific procedure that could be used in the ab initio design of aerospace vehicles. There is no procedure for calculating the structural reliability for any given number of hours of operation or for the vehicle lifetime. The analysis that is presented is essentially based on empirical data that would not be applicable to other designs. For

instance, the data on heavy bomber aircraft consists of a record of the service experience of 40 aircraft from the fleet. The time when a crack was discovered during an inspection was tabulated on Table 6. These data were converted into the probability distribution presented in Figure 19. From this the mean life to initial crack was determined to be 1970 hours. Then, on page 40 it was noted that "a crack propagation period of 60% of the total life seems realistic for the well-defined initial failure considered here. This provides an approximate estimate of 5,000 hours for the life to final failure." This estimate can be seen to stem from recorded data of operations not available during the design stage of a new vehicle. The relationship of the time to initial failure to the time to final failure appears to be based on the assumption that the crack propagation period is 60% of the total life. The uncertainties associated with the determination of this ratio can be best illustrated by the fact that on the same page a crack propagation time of 20% is suggested for fighter aircraft without any justification being presented for the two different numbers.

The remainder of the analysis in the fatigue section in Reference 15 is devoted to the determination of fatigue sensitivity which is defined as ratio of the risk of a fatigue failure under N loads to the risk of ultimate failure. Reference 43 states that the risk function "plays an important role in statistical analysis of fatigue failures." Equation (4) of Reference 41 defines reliability as a function of the integral of the risk. However, the analysis presented in Reference 15 illustrates some of the perils of a statistical approach that is dependent on analysis alone. A non-dimensional formulation of the fatigue sensitivity is presented on page 41 of Reference 15. The calculations are presented on Table 7 and on page 47 it is stated that the "life N_o for equal risk of ultimate and fatigue failure has been estimated as 960 hours." It does not seem consistent with known facts to arrive at such a number. It appears that the population defined in equation 5.3 is not the same as the population defined for the risk of fatigue failure, $r_f(N)$, when $N = 0$. This view is supported by Freudenthal's other papers. Table II of Reference 42 shows that the fatigue sensitivity factor is always equal to or greater than 1.0. Likewise on page 64 of Reference 43 it is noted that $P_F > P_U$. Then, it is stated that the risk function $r_u(N)$ is therefore not a constant but increases with N. Therefore, it appears that there is a contradiction in the analysis of the fatigue reliability as presented in the two separate papers. The discrepancy per se is not the basic problem. The basic problem is that such discrepancies may be expected to occur from time to time. If there is no quantitative procedure to verify the numerical values as computed by different analysts, there is no way to administer a structural reliability requirement by deciding that any given design does or does not comply with a specified reliability requirement.

It is suggested that in addition to the lack of recognition of the probability of errors in the analysis there is another fundamental weakness in the formulation of the structural reliability problem. This weakness resides in the abandonment of $R/S < 1.0$ as a definition of failure. Adoption of the "return period" or "life" as the basic parameter defining the structural reliability clouds the issue. The issue in question is: how likely to fail is a vehicle that is operating "now"; not will that vehicle fail at

some far distant time which it is not intended to approach. This is not a case of semantics, but something of fundamental significance.

Reference 41 on page 21 initially defines failures as $R/S<1.0$. This simply states the fact that failure occurs when the load applied is greater than the available strength. This verity is applicable at the beginning of the structural life, at all interim periods, and at the time of actual failure. In the fatigue situation, the resistance R is lower than the initial strength. As stated on page 1 of Reference 42 the "fatigue failure is, in essence, an ultimate load failure, but one involving a fatigue-damaged structure, and therefore occurring under a terminal load of considerably lower intensity...."

This principle is not used in the final formulation which reverts to the concept of "return period" or "life" as parameters that determine failure. Return period and life are abstractions that have never caused a failure. There is an implicit assumption that the distribution of the return period or life defines the distribution of the strengths that existed at previous times. There is no verification of this implicit relationship nor, in fact, is there a recognition that the relationship needs to be verified before the proposed procedures can be validated. When the relationship is established, it will be possible to decide what the successful completion of a fatigue test to a specified time means in relation to the distribution of strength and thus the reliability at some lesser time. When this information becomes available, a rational definition of the proof of compliance would then become possible. Until then, the approach will be another form of that "sophisticated deceit" warned against on page 65 of Reference 43.

Evaluation of Freudenthal's procedure by the standards listed in Section 4.3 results in the following conclusions:

1. There is no specific recommendation in References 15 and 41 through 46 for a quantitative structural reliability value that would define the Desired State for the structural system of an aerospace vehicle. Therefore no judgement can be formulated on the application of Reference 15 to actual vehicle design.

2. References 15, et al., discuss exclusively the problem of determining the structural reliability, probability of failure, or the fatigue "life" of a structure. Reference 43 acknowledges that the computed reliability figures cannot be taken at face value. Thus, they could not be used to determine <u>the</u> structural reliability. The Actual State of the structure could not be determined in such circumstances. A comparable problem exists for the fatigue mode of failure. The calculation of the "return period" or "life" does not define the probability of failure during the actual life of a vehicle. Thus, there is no procedure for calculating the reliability during the operating lifetime of the vehicle. Also, there is no discussion of a proof of compliance procedure to demonstrate the Actual State of the structure before or during operation of the vehicle.

3. Since there is no Desired State specified and there is no provision for accurately determining the Actual State, the procedure cannot furnish information for deciding whether any given structural system should be accepted or rejected for operational usage.

(8) Other Authors

The seven approaches reviewed in the previous sections represent a good cross section of the literature on the subject of quantitative structural design criteria by statistical methods. There are many other excellent papers available on the subject, but space prohibits a complete discussion of each of them. A very brief comment follows on a number of papers known to be of interest to the structural design community.

Diederich, et al., have developed the structural reliability approach presented in References 14 and 48 and other papers. The evaluation of Section 3.4 and those of the papers in this critique such as Kluger are applicable to Diederich's approach. Reference 48 introduces the Monte Carlo method to the procedure. This does not change the situation since, as Diederich says, "the statistics of the variables must be known." Contrary to the opinion of some, the Monte Carlo technique adds nothing to the formulation of the problem. All it can do is ease the solution of the particular problem formulated.

Reference 48 introduces the concept of structural optimization into the analysis, but it is only as good as the basic formulation of the problem. Sections II and III indicate that an analytical calculation of probability of failure cannot be considered to be accurate enough to serve alone as the measure of the reliability of a structural system.

In Reference 49 Switzky presents a method for "designing component members of a minimum weight structure that will have a required overall reliability." Hilton and Feigen in Reference 50 and Ghista in Reference 51 also present methods for minimizing the weight of a multi-component structural system while achieving a designated structural reliability. The optimization procedure in each of these three papers depends on the calculation of a structural reliability based on the assumption that the load and strength distributions are known.

Pugsley, in Reference 1, presented one of the earliest known discussions of the statistical approach to structural design. The summary of this report still could be used as the statement of objectives of a quantitative structural design criteria based on statistical methods. It states, "This report attempts, in a preliminary and elementary way, to bring aeroplane structural strength and loading statistics together into a logical and practical philosophy of strength factors. By correlating such statistics with structural accident rates, the influence of various design parameters is demonstrated and a new view of some past difficulties obtained." Van der Neut, in Reference 52, presented one of the first mathematical formulations of the probability of structural failure. Both of these papers were outstanding pioneering efforts and should be recognized as such.

However, neither recognized the problem that the assumed or calculated load and strength distributions are not known but are subject to errors of various magnitudes. Also, they did not recognize the need for a procedure to measure and verify the calculations that result in a decision that a particular design is acceptable.

b. Modification of Present (Factor of Safety) Structural Design System

(1) Wagner

In Reference 28 Wagner presents a brief summary of the procedures developed during an Air Force contract by Wagner, Landes, Readey and other McDonnell personnel. The complete documentation of the study is presented in Reference 10 by Landes, Wagner and Kriegshauser and in Reference 9 by Readey. Two procedures are proposed, one for immediate use and another for implementation after additional development and the collection of more data. The latter, Readey's method, was previously critiqued.

The procedure recommended in Reference 10 and summarized in Reference 28 has most of the characteristics of the Present (Factor of Safety) Structural Design System discussed and evaluated in Sections II and III. This procedure is considered to be an outstanding and pioneering effort. It recognizes both directly and intuitively many of the vital elements of a practical system of structural design based on statistical considerations. It is believed that the publication of this method is the first time anyone has seriously advocated that separate and distinct factors should be applied to each of several of the significant parameters affecting structural design.

The modified safety factor approach presented in Reference 28 incorporates many of the characteristics outlined in Section 3.6 as the desirable features of a structural design system. In particular, the procedure retains the deterministic type of requirements that give the present factor of safety system its practicality and administrability. By establishing three separate safety factors, this procedure has recognized that each significant parameter affecting the structural integrity may require a different increment or factor for design.

The fundamental problem in this procedure is the same one identified in Section III for the Present Structural Design System. There is no clearly identifiable objective that the Present System and the system proposed in Reference 28 is expected to satisfy. The present requirements have evolved, for the most part, as a reaction to past problems. The Reference 28 proposal would not change this situation. The choice of 1.05, 1.10, and 1.15 as factors to apply to speed, quality, and maneuverability is justified initially on the basis that the resulting design approximates that which would result from the typical missile factor of safety of 1.25. As Wagner says, "the proof of this modified approach can be achieved <u>only</u> through its use." This is exactly how the Present System has evolved. Once these factors were adopted, they would not be changed unless some future failure occurred that indicated an inadequacy in the requirement. In such an event, an ad hoc decision would be generated to define the change required.

If this same procedure were to be applied to manned aircraft, the basis for the choice of the three parameters is not clear. Since all classes of aircraft presently require the same 1.5 factor of safety, presumably all would have the same three factors for speed, quality and maneuverability. However, a light observation plane, a fighter and a transport probably would not require the same factor for speed. The rationale for choosing different values would have to be defined.

In the proposed procedure of Reference 28 limit loads do not exist. If there are no limit loads, there can be no limit operational conditions. If such is the case, then there are no operational limitations that can be furnished to the user of the vehicle. It is considered that the establishment of a common point of reference for the user and designer is vital to the success of the Present System. Any new system should identify explicitly the crucial interfaces with non-structural systems. It should make provision for assigning responsibility for every function that affects structural integrity. The limit conditions furnish an unequivocal line of demarcation between the responsibilities of the structural system designer and the vehicle user. Regardless of how a limit condition is established, it is permissible for the user to operate up to that limit. At this level the structural system should be safe and "never" fail. Above the limit condition the responsibilities shift. The user is violating his stated restrictions anywhere above limit conditions and must expect that failure will occur if the excursion beyond limit becomes very large.

Figure 10 shows how Limit Design Conditions are the basis for Operational Limitations. In turn, these become part of the Operational System where they play a vital part in determining the frequency of operational failures. Certainly, the vehicle user who has been informed of the safe operating limits and is trying to observe these limits will experience fewer failures than the uninformed user. Abandonment of the concept of limit conditions would have to be considered to be a serious deficiency in the proposed procedure.

In many cases there is no direct user control of the vehicle, as in the case of missiles for which Reference 28 was developed. Even so, limit conditions should be defined to establish the interface that represents the upper limit of the normal or expected situation for each non-structural system. As discussed on page 47, the cause of any failure at limit condition or less unquestionably resides somewhere in the structural system. The capability to make such decisions contributes to the practicality and administrability of the Present System.

A statement is made in References 10 and 28 that bears on the basic philosophy of the function of structural design criteria. As such it warrants a thorough discussion, even though the statement itself is relatively unimportant to the understanding of the procedure. The statement indicates that by the use of a separate factor on speed, "the designer is forced to avoid the use of materials which are unduly sensitive to temperature changes." The designer may recognize this sensitivity as undesirable but be impelled to use the particular material by other requirements. Structural design criteria should never arbitrarily proscribe the use or avoidance of a

particular material or structural configuration. Criteria should specify the "performance" required of the structure in such a way that any material could be used. The cost in weight or dollars that must be paid to obtain the specified "performance" may make it very logical to choose one material over another but the designer should have the option to make the decision.

Reference 28 notes that "if the allowable load is subject to variation or error due to tolerances, speed, and angle of attack, it is logical to provide for these possible errors." It is a common misconception to treat the fact that there exists a variation in some quantity affecting a structural system as though the variations were due to errors. An error implies a departure from what is right or proper, possibly even carelessness. There is a variation in the height of humans, but this variation represents the expected or normal situation. There is no error involved. In the same vein, a variation in sheet thickness between the tolerance values could not be considered to be an error. It is part of the typical production process of rolling a sheet considering wear on rolls and the spring of the rolls at the center and the process of deciding when to stop a production run and readjust the mill. On the other hand, any material that was half the specified dimension would be the result of an error. It would not be a proper variation and carelessness would presumably be involved.

Proper appreciation of this concept is vital to the determination of exactly what should be considered in the design of a structural system. It would be the grossest kind of negligence for the structural designer and analyst to ignore expected variations in structural parameters. However, there should be a very limited obligation to make provisions for the structural system to tolerate and survive errors in the fabrication, maintenance and operation of the vehicle system, including errors in the performance of non-structural systems. As indicated in the evaluation of the Present System in Section III, it is one of its deficiencies that the Present System does not clearly delineate those errors in non-structural systems that are obligatory for the structural system to survive from those it is not expected to survive.

The most significant concept in the approach as outlined in Reference 28 is the idea that the structural design should consider ultimate conditions. Such a concept represents a break with the past. Since the adoption of factor of safety as a concept, structural design criteria have not required (except in special cases) that the structure be responsible for any specific operational conditions beyond those specified as limit conditions. Adoption of a policy that the structural system does have such a responsibility should not be done without serious consideration of all the ramifications. The concept has much logic behind it and was, in fact, recommended by the authors of this critique in References 4 and 5. Implementation of the concept would be subject to many serious problems. It is questionable whether the applied loads (i.e., the loads that actually occur) at ultimate conditions can be accurately computed using present state-of-the-art methods. The calculations would necessarily include the effects of yielding which would affect the aeroelastic situation. The ultimate condition might represent an unstable condition in which it would be difficult to decide how to balance the forces acting on the vehicle. There would inevitably be questions on how quickly the vehicle traversed

the range from limit to ultimate conditions since this would affect the temperature transients on the structure and the failing strength of the structure.

Verification of the computed loads would be a difficult if not impossible objective of a test program. In the extreme, each ultimate condition verified might result in the loss of the test vehicle. Proof of compliance, which is emphasized throughout Section III as vital, might be impractical for all classes of vehicles but particularly for manned vehicles. If the verification of ultimate conditions and ultimate loads by flight test is not feasible and if there is no limit condition defined that could be verified, there is no objective basis for deciding what constitutes a fully qualified structural system. Until the question is examined in all its aspects and used in the design of many vehicles, not just to one flight vehicle, universal adoption of the concept might be akin to opening Pandora's Box. Finally, the cost involved in implementing the procedure in the design of any new vehicle would undoubtedly be significantly greater than under the Present System. This of course, is a major consideration in the practicality of the procedure.

Evaluation of the modified factor of safety procedure by the standards listed in Section 4.3 results in the following conclusions:

1. The procedure does not have a clearly-defined quantitative objective that is expected to be satisfied. The three factors suggested are empirical and may or may not produce a satisfactory structural system. Once adopted, the three factors would become so embedded in specifications that there would be no way to justify any changes to the values. One of the problem areas in the Present System where the Reference 28 procedure offers an improvement is the question of the design temperatures for the structure.

2. The Actual State of the structural system would be determined in much the same manner as described in Section II and as shown on Figure 10. The evaluation of the Actual State Information System for the Present (Factor of Safety) Structural Design System in Section III would be applicable generally to the procedure. The Strength Test Stage shown on Figure 13 could be accomplished in much the same fashion as at present. The Flight Test Stage would necessarily be changed and there would be no specific flight conditions that could be demonstrated nor would there be a specifiable verification of design loads anymore.

3. The procedure will be about the equivalent of the Present System as evaluated in Section III for capability to provide an early disclosure of possible strength discrepancies between Desired State and Actual State. Since it will not usually be feasible to compare Actual Loads at specified design conditions with the Desired State loads, there can be no comparison and disclosure of error. The

procedure will be severely handicapped because of this loss in error disclosure capability.

Although differences of opinion regarding the procedure were noted, it should be understood that this procedure is considered to be the best — the most practical — the most logical — of all the papers reviewed in this critique. Reference 28 is one of the few recognizing either explicitly or implicitly, most of the elements associated with a completely rational, and objective structural design system.

4.5 SUMMARY OF CRITIQUES

Fourteen different approaches to the problems of structural reliability, structural design criteria and structural design procedures have been evaluated in this critique. These papers are considered to be a representative cross section of the methods extant in the technical literature. All but one of the documents evaluated have the common characteristic of considering that the calculated or assumed load and strength distributions are "known" distributions. As such, these approaches can be categorized as Purely Statistical Structural Reliability Systems as described in Sections II and III. The remaining paper is categorized as a modification of the Present (Factor of Safety) Structural Design System described in Sections II and III.

The thirteen papers that are grouped together as Purely Statistical Structural Reliability Systems have the same characteristics as the basic system of this type. As a result, the evaluation in Section 3.4 is generally applicable to each of the thirteen papers. In that section it was noted that the principal deterrent to the adoption of a Purely Statistical Structural Reliability System is the fact that there is no procedure available for accurately determining the actual structural reliability of a particular structural design. Analytical calculation is not sufficiently accurate to serve as the sole determinant of structural reliability. Experimental determination of structural reliability is not feasible for the structural reliabilities usually considered for aerospace vehicles. As a result, there is no proof of compliance technique that would be satisfactory for demonstration that a contractual requirement had been fulfilled. None of the approaches critiqued in Section 4.4a contain any solution to the problem, so it must be considered that none of these procedures is practical for the design of aerospace vehicles.

In summarizing the critique of the 14 papers by the standards of Section 4.3, it is apparent that most of the papers have similar characteristics. Nearly all of the papers have defined the Desired State in terms of a quantitative value for structural reliability. As discussed in the critique of Reference 11 which is applicable to most of the other papers, there are two common problems in defining structural reliability as the Desired State. One is to formulate a rational basis for the choice of a particular number for structural reliability. The other is the precise meaning of structural reliability. The discussion on page 78 points out that there are three orders of reliability. These are the reliabilities for an individual vehicle, those for the group of nominally identical vehicles of a particular design, and the general reliability of all vehicles of all

designs resulting from following the precepts of a particular design system. While it is considered that these two questions must be resolved in the development of quantitative structural design criteria by statistical methods, there should be no great difficulty in doing so.

Several of the procedures present an additional requirement that the required structural reliability be converted into a total probability of failure which is allocated to the individual components of the structural system. Where this approach is followed, there is an implicit assumption that the probability of failure of the total system is equal to the sum of the probabilities of failure of the individual components. The assumption is not a tenable one in most structural situations. It is not generally recognized that the increment a single component contributes to the total must be based on a conditional reliability. This conditional reliability is expressed as the probability of failure of the component given that all the other components have survived. The problem is discussed at length on page 104.

Two of the papers, References 28 and 29, define design ultimate loads directly from operational conditions rather than as limit loads multiplied by a Factor of Safety. Reference 28 specifically defines ultimate conditions. Such a concept represents a break with the past. Adoption of a policy that the structural system has an explicit responsibility to survive beyond specified limit conditions should not be done without serious consideration of all the ramifications, some of which are discussed on page 118. The idea of defining ultimate loads directly rather than as factored limit loads retains the advantage of presenting the structural design criteria in a deterministic form that can be administered. Reference 29 uses a rational probability analysis technique for defining the Design Ultimate Load. The basic philosophy of defining the ultimate conditions from statistical considerations but designing to these conditions as deterministic requirements is undoubtedly the most rational and practical approach available.

Several of the papers reviewed in the critique expressed the thought that it is desired that the structural system survive all loads that may be encountered. Such an objective is unrealistic if the structural system is to be light enough to permit the vehicle to perform a useful function. It should not be the function of the structure to survive <u>any</u> conceivable gross overload including situations precipitated by failure of non-structural systems. Neither should it be the intention that the structure should tolerate <u>any</u> conceivable gross error in the design, fabrication and maintenance of the structure. Structural design criteria should identify and define the interfaces with non-structural systems. It should be the responsibility of the structural system to prevent vehicle failures for a limited range of operational conditions and the responsibility of other non-structural systems to prevent vehicle failures outside the range by avoiding conditions the structure cannot survive.

SECTION V

CONCLUSIONS

Present and proposed approaches to structural design criteria are evaluated in this critique. The evaluation is accomplished in three steps. First, a discussion and analysis is presented to develop an understanding of the various functions that contribute to a structural design system. Second, standards of evaluation are established and two basic structural design systems are evaluated by these standards. Third, a group of papers, considered to be a representative cross section of the structural reliability methods extant in the technical literature, are reviewed and compared to the two basic systems.

Section II introduces Professor Draper's informetics concept to the study of structural design systems. This concept provides the framework for clarifying the purpose of the various functions that contribute to a structural design system. It also provides an unparalleled opportunity to dispassionately discuss the strong points and weaknesses of each system. It is expected that this type of analysis will illuminate the structural design problem and will be most useful when it is applied to future proposals for changing the present structural design system.

Section III converts the understanding of the functions of a structural design system into an evaluation of the merits and the problem areas associated with the two basic structural design systems. These two systems are the Present (Factor of Safety) Structural Design System and a hypothetical Purely Statistical Structural Reliability System.

In Section III it is concluded that the Present (Factor of Safety) Structural Design System is a generally satisfactory system for the design of aerospace vehicles. However, there are some problem areas that will become more apparent as advanced missions require the use of new structural configurations and materials. A Purely Statistical Structural Reliability System is not practical for the design of aerospace vehicles. Since there is no way to accurately measure structural reliability, it is not possible to write a definitive contract requiring demonstration of a specified structural reliability.

The fundamental problem area in the Present System resides in the fact that there is no clearly identifiable, quantitative objective that the Present System is expected to satisfy. In most cases a high degree of structural integrity has resulted from an indirect and sometimes intuitive consideration of those characteristics that are a prerequisite to consistent structural survival. Such things as ductile materials and a general insensitivity to minor discrepancies in the structure have been provided by state-of-the-art structural practices. In those few cases where problems did occur, the requirements were changed in reaction to the problem. There is an implicit assumption that future structural systems will have the same characteristics as past systems. This is not necessarily a valid assumption. In particular, current trends indicate that many future systems will have a

much larger coefficient of variation in strength than has been customary in the past. Also, most space vehicles will not receive the extensive flight loads testing that has been customary with aircraft. Both of these conditions tend to degrade the power of the strength and loads tests to disclose errors in the analysis.

Another result of the lack of a clearly identifiable objective is that there is no logic available that can resolve questions such as a request to lower the factor of safety from 1.5 to 1.4. There is great need for a criterion by which to judge such questions objectively.

In some of the newer structural design areas, such as fatigue and high temperatures, the factor of safety concept is not directly applicable to the definition of structural design requirements. There is even more need to clearly define the objectives of the structural design system for these problems than there is for the problems that the Present System conventionally considers. Coupled with the definition of an objective must be practical procedures for determining the Actual State and for proof of compliance with the stated objectives.

In situations where a structural failure does occur, the deterministic nature of the Present System permits the determination of a cause of failure, responsibility for the failure, and corrective action. However, many of the interfaces between the structural system and other systems are not explicitly defined. Therefore, responsibility for some of the areas contributing to structural integrity is not recognized until after a failure occurs.

The principal deterrent to the adoption of a Purely Statistical Structural Reliability System is the fact that there is no procedure for accurately determining the actual structural reliability of a particular structural design. As a result there is no proof of compliance technique that would be satisfactory for demonstration that a contractual requirement has been fulfilled.

As a derivative of the problem of determining the value representing the actual structural reliability of a vehicle, there is the problem of determining a cause and assigning responsibility when structural failures do occur. When cause and responsibility are not determinable, neither is the corrective action.

In Section IV, fourteen documents on the subject of structural reliability and structural design criteria are evaluated. All but one of the documents evaluated have the common characteristic of assuming that the calculated or assumed load and strength distributions are known distributions. As such, these approaches can be categorized as a Purely Statistical Structural Reliability System. In Section III it is concluded that such a system is not practical for the design of aerospace vehicles.

The procedure, defined in References 10 and 28, is a modified factor of safety approach. In the discussion of the procedure, it is concluded that the approach is considered to be the best — the most practical — the most logical — of all the papers reviewed in this critique. This

paper is one of the few recognizing, either explicitly or implicitly, most of the elements associated with a completely rational and objective structural design system. However, the detail evaluation discusses several problems associated with the procedure that prevent an acceptance of the procedure in its present form as a valid, practical method for the definition of quantitative structural design criteria by statistical methods.

As a result of the evaluation of 14 different presentations of approaches to the structural reliability problem, this critique concludes that none of the known approaches in the literature today provides a satisfactory foundation for quantitative structural design criteria based on statistical methods.

If it is desired to provide the Present System with a quantitative objective and with the capability to systematically resolve the problems associated with structures for advanced vehicles, a new structural design system is needed. The new procedure should retain the deterministic type of requirements that give the Present System its practicality and administrability. The deterministic requirements can be established in such a way that they correspond to a structural reliability goal without having to prove directly that the goal has been achieved. In such an approach, all of the elements affecting structural reliability can be consistently directed towards achieving a quantitatively-defined structural reliability goal without introducing the impossible problem of proving compliance with a structural reliability requirement. Nine characteristics that should be incorporated in a modification of the Present System are recommended in Section 3.6, page 72. The procedure described in Volumes II and III of this report was developed with the intention of satisfying the recommendations of Section 3.6.

APPENDIX

The behavior of the numerical value of the probability of failure (P_F) as a function of the coefficient of strength variation (γ_s) and other significant parameters is often considered to be rather mysterious by those who have not had the opportunity to study the question carefully. As a result, the P_F calculations necessary for any structural reliability (SR) calculation are often viewed with a somewhat jaundiced eye by the practical engineer. Experience has shown that it is relatively easy to explain the behavior of P_F curves of which those on Figure 23 in Section 4.4a(4) are typical. Values for these curves were generated by the computer program described in Volume III. The technical background for this program is developed in Section 2.3 of Volume II.

Curve (1) is the simplest to explain so this will be considered first. It is assumed that the load and strength distributions are known; that is, there is no analytical error. This condition is represented by inputting the control number K2 = 11. As explained in Volume III, the program then computes the P_F with a routine appropriate to that assumption. All of the values on Figure 23 are based on a loading spectrum which has its mean at the limit load and which has a probability of exceeding the ultimate, or omega load, of 10^{-3}. Limit load is assumed to have a value of 100 and the typical factor of safety of 1.5 means that the ultimate load is 150. The probability of exceeding the load at various levels is printed out as PELXI for the various cases shown on Figures A-1 through A-7. Since the computer program prints out only in the region that contributes significantly to the total P_F, Figure A-1 does not show that PELXI is 0.5 when XI is 100. However, this is shown on Figure A-4 which has the same loading distribution. Figure A-1 does show that the probability of exceeding the ultimate load at 150 is .001, which is consistent with the assumptions on which Figure 23 is based.

Case 1, Figure A-1, represents a situation where the γ_s is very small — approaching zero. The basic assumption is that the strength allowable is a 99-percent-exceed value, as indicated by SIGALL equal to 2.3263 (note Figures 5 and 6 in Volume 3). This value is matched to the ultimate load of 150 so the mean strength is slightly higher as shown by the printout of AMUT equal to 150.3497 for Case 1. Most of the systems of this design would have their strengths between the upper and lower 99-percent levels of the strength distribution. The lower level is already established at 150 and the upper level is the same distance on the other side of the mean or at 150.6994. Most of the contribution to the total P_F should be between these two values. Note in Case 1 that only 1006 out of the total of 92612 units, or about one percent, is contributed to the total up to XI equal to 149.99. The P_F at 150.71 is already 92032 of the total of 92612 so less than one percent is added beyond that point.

Since almost all the strength is concentrated very close to the ultimate load of 150 which has a probability of being exceeded of 10^{-3}, the probability

of failure is close to 10^{-3}. The left hand end of Curve (1) on Figure 23 approaches 10^{-3} as γ_s approaches zero.

As γ_s becomes larger the situation changes somewhat. Case 2, Figure A-2, shows this. When γ_s equals 0.03 the mean strength must be higher than 150 in order to have the 99-percent-exceed strength at 150. Case 2 shows AMUT as 161.2537. The strength range is now from 150 to 172. If the strength is imagined to be concentrated temporarily all at the mean (161), where PELXI is about 10^{-4}, the P_F would be that value. Actually, the loads on the low side of the mean are more likely to be exceeded than those on the high side. As a result, the strengths on the low side of the mean add to P_F more rapidly than those on the high side subtract from the value that would be obtained if all the strengths were at the mean. The total P_F increases somewhat and the distribution of the failures shifts so it is not centered about the mean strength, but rather is on the low side of the mean. The range of the failure distribution is now between about 145 and 165. Thus, the mean of the failure distribution has moved up from approximately 150.3 for Case 1 to 155 for Case 2, and the range of significant contribution to the P_F value has widened out substantially for Case 2. Very roughly, the P_F could be estimated by assuming that the effective mean strength is about half-way between the true mean of 161 and the 99-percent-exceed point at 150. PELXI at this half-way point is 3×10^{-4} which is a reasonable approximation of the value computed for Case 2 with γ_s equal to 0.03. This may help explain why P_F decreases initially as γ_s increases from zero.

As γ_s continues to increase, Figure 23 shows that P_F reaches a minimum on Curve (1) when γ_s is approximately 0.07. Case 3, Figure A-3, shows this situation. The mean continues to increase in order to hold the 99-percent-exceed allowable at 150. For this case AMUT equals 179.1774. The range where most of the failing strengths are concentrated is now from 150 to about 208. If all the strengths were concentrated at the mean where PELXI is about 5×10^{-7}, the P_F would be that value. As noted before, the loads on the low side of the mean are very much more likely to be exceeded than those on the high side. Therefore, the contributions to P_F reach a peak near 149.50 as shown by the DELPF increments on Figure A-3. The load probabilities from 179 on up are more than three orders of magnitude lower than they are at 150, so the probability of failure in this region becomes negligible relative to the total P_F. As a result, the failure distribution is essentially from 125 to 175. If all the strengths were concentrated at about 162 where PELXI is about 5×10^{-5}, the P_F would be this same value. Since this is the P_F shown in the computations of Figure A-3, the effective strength again is close to the half-way point between the 99-percent-exceed point and the mean strength. This rule of thumb furnishes a reasonable approximation of P_F as long as γ_s is relatively small.

These three cases show that it is reasonable and to be expected for the P_F to decrease as γ_s increases as long as γ_s remains relatively low (below 0.10, for example). This decrease in P_F is due to the movement of the mean strength to higher values which are less likely to occur. However, even in Case 3 where γ_s equals 0.07, the contribution of failures below 150 have become over half the total. As γ_s continues to increase this trend is accelerated. As the mean continues to move higher and the probability of

attaining a load high enough to cause a failure in the vicinity of the strength mean becomes very low, more and more of the failure distribution occurs at very low values of XI.

Case 4, where γ_s equals 0.24, illustrates this situation. It should be noted that the mean must be at 339.6060 in order to place the 99-percent-exceed value at 150. As a result a negligible amount of the total P_F is contributed by those strengths above 150, even though 99 percent of the strengths are in this region. From the geometry of the Gaussian distribution the area below the 100 value corresponds to 0.0016. The probability of exceeding this load is 0.5 so the incremental P_F up to 100 must be at least 0.5 x 0.0016 = 0.0008. Since the values of PELXI below 100 are greater than 0.5 and approach 1.0, the incremental P_F should be somewhat larger than 0.0008. The printout on Figure A-4 shows it is about 0.0013. It can be seen that the failure increment below 100 is already over 20 times the total P_F when γ_s equals 0.07. Thus, it must be realized that when γ_s becomes large, most of the failures are due to those strengths which are less than 100. This accounts for the rise in P_F between the γ_s values of 0.07 and 0.24 as shown on Figure 23. Incidentally, if γ_s increased still further, the proportion of strengths below 100 would increase still more and P_F would continue to rise. However, 99 percent of the strengths exceed 150 by the conditions of the problem so this sets an upper limit on P_F. The number below 100 must always be less than 0.01, so the incremental P_F must be less than 0.01. This means that as Curve (1) on Figure 23 is extended to the right, it would become assymptotic to and below the 10^{-2} line.

The reason Curve (2) on Figure 23 is so high is because of the introduction of consideration of the probability that there will be errors in the strength analysis. This means that the actual mean strength of the structural system may be much below the intended strength. This situation is discussed at great length in Volumes II and III. Suffice it to say here, that it is assumed that the error function is the same as in the past as defined on Figure 5 of Volume II. This indicates that about 13 percent of the designs will fail at limit load or less on their first loading after analytical design. If such designs are used in operational vehicles without the benefit of strength testing, the same percentage could be expected to fail at limit load or less during operations. By the same reasoning as used in Case 3, it can be concluded that the incremental failure rate up to 100 should be greater than 0.5 x 0.13 = 0.065. The value shown on Figure A-5 is about 0.09 with the total being 0.124. The basic phenomenon here is that, when there is no strength test to disclose errors, the total probability of failure is closely tied in to the probability that there will be an analytical error large enough to bring the mean strength below the limit load. This error function represents a completely different distribution than the strength distribution about a known mean strength. Accordingly, P_F for the situation where strength errors in analysis are recognized and integrated into P_F becomes essentially independent of γ_s as shown on Curve 2 of Figure 23 when no strength tests are conducted.

Curve 3 represents the typical situation for aerospace vehicles. The error function is included but one strength test is conducted which will disclose the analytical errors with varying degrees of certainty depending on γ_s. Case 6, Figure A-6, shows the improvement in P_F from Case 5. It is

not as good as Case 3 where perfect analytical accuracy is assumed but the P_F is 0.00114 which is only slightly higher than the desired value of 10^{-3}. The basis for the decrement in P_F from Curve (2) to Curve (3) on Figure 23 is discussed in Section 2.3d(1) of Volume II and represented pictorially on Figure 10 of that volume. It is noted therein that it becomes highly unlikely that a system whose mean is at 100 will survive the strength test to 150. The error is disclosed with a high degree of certainty. Case 6 reflects this since the incremental P_F at 100 is about 10^{-5} whereas in Case 5 with no test the value is 0.09.

As noted in the discussion in Section 2.3d(2) of Volume II, the error disclosure is much less certain when γ_s is large. As a result, the incremental P_F at 100 increases to 0.0087 when γ_s is 0.24 and the total P_F is 0.0135. Most of the failures in this situation occur between 60 and 120. They are due to structures whose mean is near 120, which would mean that there is a 0.15 probability of surviving the test to 150 even though the mean at 120 is only about one-third of the intended value of 339.6060. This relatively high chance of an understrength design passing the test to ultimate load accounts for the significant increase in P_F as γ_s goes from 0.07 to 0.24. Section 2.3d(3) of Volume II discusses how this difficulty is overcome by testing to a load higher than 150 when γ_s is large.

STRUCTURAL RELIABILITY

ANALYSIS

CASE 1

INPUT DATA

STRUCTURES

AMUT	GAMS	TESTES	ULTTST	SIGALL
150.3497	0.0010	1.0000	150.0000	2.3263
FS	MS	DF	DSGNLD	NTEST
1.500	0.0	1.000	150.0000	0
ACFAC				
INFINITY				

LOADS

AMUL	GAML	LIMLD	ULTLD
100.000	0.16181	100.00000	150.[illegible]000

PROGRAM CONTROLS

DELXI	DELXJ	DELXK	DELXIA	DELXIB
0.0200	0.5000	3.4500	10.0000	5.0000
SIGLIM	SLIM	WRTSKP	PFEXP	PFEND
5.00	172.4999	4.	0.10000E-05	0.10000E-02
XJA	XJB	XJKCON	XJKINC	
10.	5.	6.	20.	

KEY

K1	K2	K3	K4	K5
1	11	21	31	41

FIGURE A-1. NO ANALYTICAL ERROR (γ_s = 0.001)

CASE 1

OUTPUT DATA

XI	PELXI	STRDUF	DELPF	PF
149.51	0.111264E-02	0.44533E-06	0.99099E-11	0.00000000
149.59	0.109407E-02	0.75495E-05	0.16519E-09	0.00000000
149.67	0.107568E-02	0.96380E-04	0.20735E-08	0.00000000
149.75	0.105746E-02	0.92750E-03	0.19616E-07	0.00000005
149.83	0.103941E-02	0.67248E-02	0.13980E-06	0.00000036
149.91	0.102152E-02	0.36735E-01	0.75050E-06	0.00000217
149.99	0.100379E-02	0.15118E 00	0.30351E-05	0.00001006
150.07	0.986203E-03	0.46879E 00	0.92464E-05	0.00003610
150.15	0.968908E-03	0.10952E 01	0.21222E-04	0.00010123
150.23	0.952063E-03	0.19276E 01	0.36705E-04	0.00022470
150.31	0.935645E-03	0.25562E 01	0.47833E-04	0.00040219
150.39	0.919626E-03	0.25540E 01	0.46975E-04	0.00059562
150.47	0.903986E-03	0.19226E 01	0.34761E-04	0.00075547
150.55	0.888707E-03	0.10905E 01	0.19382E-04	0.00085562
150.63	0.873769E-03	0.46596E 00	0.81429E-05	0.00090319
150.71	0.859155E-03	0.15001E 00	0.25777E-05	0.00092032
150.79	0.844849E-03	0.36387E-01	0.61483E-06	0.00092499
150.87	0.830836E-03	0.66496E-02	0.11050E-06	0.00092595
150.95	0.817105E-03	0.91593E-03	0.14968E-07	0.00092610
151.03	0.803636E-03	0.95018E-04	0.15272E-08	0.00092612
151.05	0.800309E-03	0.51586E-04	0.82569E-09	0.00092612

THE FACTOR OF SAFETY FOR CASE 1 IS 1.500

NO STRENGTH TEST NECESSARY WITH ASSUMPTION OF PERFECT ANALYTICAL ACCURACY.

THE THEORETICAL STRUCTURAL RELIABILITY OF CASE 1 IS 0.99907392

FIGURE A-1. (Concluded)

CASE 2

INPUT DATA

STRUCTURES

AMUT	GAMS	TESTFS	ULTTST	SIGALL
161.2537	0.0300	1.0000	150.0000	2.3263
FS	MS	DF	DSGNLD	NTEST
1.500	0.0	1.000	150.0000	0
ACFAC				
INFINITY				

LOADS

AMUL	GAML	LIMLD	ULTLD
100.000	0.16181	100.00000	150.00000

PROGRAM CONTROLS

DELXI	DELXJ	DELXK	DELXIA	DELXIB
1.0000	0.5000	3.7088	10.0000	5.0000
SIGLIM	SLIM	WRTSKP	PEEXP	PFEND
5.00	185.4417	4.	0.10000E-06	0.10000E-72
XJA	XJB	XJKCON	XJKINC	
10.	5.	6.	20.	

KEY

K1	K2	K3	K4	K5
1	11	21	31	41

FIGURE A-2. NO ANALYTICAL ERROR (γ_s = 0.03)

CASE 2

OUTPUT DATA

XI	PELXI	STRDNF	DELPF	PF
130.50	0.297990E-01	0.0	0.0	0.00000000
134.50	0.165343E-01	0.18726E-07	0.31061E-09	0.00000000
138.50	0.869294E-02	0.12922E-05	0.11233E-07	0.00000002
142.50	0.432261E-02	0.44862E-04	0.19302E-06	0.00000039
146.50	0.202824E-02	0.78616E-03	0.15945E-05	0.00000396
150.50	0.898295E-03	0.69539E-02	0.62466E-05	0.00002088
154.50	0.376197E-03	0.31047E-01	0.11680E-04	0.00006070
158.50	0.149017E-03	0.69967E-01	0.10426E-04	0.00010727
162.50	0.558371E-04	0.79587E-01	0.44439E-05	0.00013434
166.50	0.197891E-04	0.45695E-01	0.90426E-06	0.00014215
170.50	0.663074E-05	0.13243E-01	0.87808E-07	0.00014326
173.50	0.275615E-05	0.33396E-02	0.92045E-08	0.00014334

THE FACTOR OF SAFETY FOR CASE 2 IS 1.500

NO STRENGTH TEST NECESSARY WITH ASSUMPTION OF PERFECT ANALYTICAL ACCURACY.

THE THEORETICAL STRUCTURAL RELIABILITY OF CASE 2 IS 0.99985671

FIGURE A-2. (Concluded)

CASE 3

INPUT DATA

STRUCTURES

AMUT	GAMS	TESTFS	ULTTST	SIGALL
179.1774	0.0700	1.0000	150.0000	2.3263
FS	MS	DF	DSGNLD	MTEST
1.500	0.0	1.000	150.0000	0
ACFAC				
INFINITY				

LOADS

AMUL	GAML	LIMLD	ULTLD
100.000	0.16181	100.00000	150.00000

PROGRAM CONTROLS

DELXI	DELXJ	DELXK	DELXIA	DELXIB
1.0000	0.5000	4.8378	10.0000	5.0000
SIGLIM	SLIM	MRTSKP	DFEXP	DFEND
5.00	241.8894	4.	0.10000E-08	0.10000E-02
XJA	XJB	XJKCON	XJKINC	
10.	5.	6.	20.	

KEY

K1	K2	K3	K4	K5
1	11	21	31	41

FIGURE A-3. NO ANALYTICAL ERROR ($\gamma_s = 0.07$)

CASE 3

OUTPUT DATA

XI	PELXI	STRDMF	DFLPF	PF
105.50	0.367265E 00	0.10196E-08	0.37445E-09	0.00000000
109.50	0.278676E 00	0.63088F-08	0.17581F-08	0.00000000
113.50	0.202047E 00	0.35261E-07	0.71245E-08	0.00000002
117.50	0.139796E 00	0.17802F-06	0.24887E-07	0.00000009
121.50	0.920750F-01	0.81187F-06	0.74753F-07	0.00000030
125.50	0.575877F-01	0.33445F-05	0.19260E-06	0.00000086
129.50	0.341318E-01	0.12445F-04	0.42477E-06	0.00000217
133.50	0.191639E-01	0.41830F-04	0.80163E-06	0.00000478
137.50	0.102698E-01	0.12700F-03	0.13043E-05	0.00000922
141.50	0.520596E-02	0.34831E-03	0.18133E-05	0.00001570
145.50	0.248150E-02	0.86287E-03	0.21412F-05	0.00002380
149.50	0.111050E-02	0.19309E-02	0.21442F-05	0.00003247
153.50	0.468049E-03	0.39029E-02	0.18268E-05	0.00004041
157.50	0.188375F-03	0.71262F-02	0.13424F-05	0.00004665
161.50	0.736499F-04	0.11753E-01	0.86562F-06	0.00005032
165.50	0.267262F-04	0.17510F-01	0.46797F-06	0.00005318
169.50	0.895268E-05	0.23563E-01	0.21095E-06	0.00005433
173.50	0.278026E-05	0.28642F-01	0.79633E-07	0.00005482
177.50	0.812261E-06	0.31450E-01	0.25545E-07	0.00005499
181.50	0.234431E-06	0.31193F-01	0.73126E-08	0.00005505
185.50	0.676827E-07	0.27946E-01	0.18915E-08	0.00005506
187.50	0.311700F-07	0.25462F-01	0.79305E-09	0.00005506

THE FACTOR OF SAFETY FOR CASE 3 IS 1.500

NO STRENGTH TEST NECESSARY WITH ASSUMPTION OF PERFECT ANALYTICAL ACCURACY.

THE THEORETICAL STRUCTURAL RELIABILITY OF CASE 3 IS 0.99994498

FIGURE A-3. (Concluded)

CASE 4

INPUT DATA

STRUCTURES

AMUT	GAMS	TESTFS	ULTTST	SIGALL
339.6060	0.2400	1.0000	150.0000	2.3263
FS	MS	DF	DSGNLD	NTEST
1.500	0.0	1.000	150.0000	0
ACFAC				
INFINITY				
		LOADS		
AMUL	GAML	LIMLD	ULTLD	
100.000	0.16181	100.00000	150.00000	
		PROGRAM CONTROLS		
DELXI	DELXJ	DELXK	DELXIA	DELXIB
1.0000	0.5000	14.9427	10.0000	5.0000
SIGLIM	SLIM	VRTSKP	PFEXP	PFEND
5.00	747.1326	10.	0.10000E-05	0.10000E-04
XJA	XJB	XJKCON	XJKINC	
10.	5.	6.	20.	
		KEY		
	K2	K3	K4	K5
	11	21	31	41

FIGURE A-4. NO ANALYTICAL ERROR (γ_s = 0.24)

CASE 4

OUTPUT DATA

XI	PELXI	STRDNF	DELPF	PF
0.50	0.100000E 01	0.85088E-06	0.85088E-06	0.00000085
10.50	0.100000E 01	0.14070E-05	0.14070E-05	0.00001220
20.50	0.999999E 00	0.22918E-05	0.22918E-05	0.00003081
30.50	0.999984E 00	0.36772E-05	0.36772E-05	0.00006084
40.50	0.999774E 00	0.58121E-05	0.58108E-05	0.00010861
50.50	0.998998E 00	0.90490E-05	0.90400E-05	0.00018340
60.50	0.991566E 00	0.13878E-04	0.13761E-04	0.00029833
70.50	0.962644E 00	0.20967E-04	0.20184E-04	0.00047021
80.50	0.889565E 00	0.31263E-04	0.27632E-04	0.00071276
90.50	0.709738E 00	0.45742E-04	0.32465E-04	0.00101947
100.50	0.495890E 00	0.66054E-04	0.32755E-04	0.00135050
110.50	0.259037E 00	0.93960E-04	0.24339E-04	0.00163973
120.50	0.108026E 00	0.13166E-03	0.14223E-04	0.00182690
130.50	0.298938E-01	0.18173E-03	0.54326E-05	0.00191647
140.50	0.711754E-02	0.24709E-03	0.17587E-05	0.00194982
150.50	0.130894E-02	0.33095E-03	0.43319E-06	0.00195735
160.50	0.980377E-04	0.43663E-03	0.42806E-07	0.00195906
170.50	0.143559E-04	0.56746E-03	0.81465E-08	0.00195930
180.50	0.100117E-05	0.72648E-03	0.72733E-09	0.00195931
187.50	0.225814E-07	0.85592E-03	0.19328E-10	0.00195931

THE FACTOR OF SAFETY FOR CASE 4 IS 1.500

NO STRENGTH TEST NECESSARY WITH ASSUMPTION OF PERFECT ANALYTICAL ACCURACY.

THE THEORETICAL STRUCTURAL RELIABILITY OF CASE 4 IS 0.99804074

FIGURE A-4. (Concluded)

CASE 5

INPUT DATA

STRUCTURES

AMUT	GAMS	TESTFS	ULTTST	SIGALL
179.1774	0.0700	1.0000	150.0000	2.3263
FS	MS	DF	DSGNLD	NTEST
1.500	0.0	1.000	150.0000	0
ACFAC				
1.00				

LOADS

AMUL	GAML	LIMLD	ULTLD
100.000	0.16181	100.00000	150.00000

PROGRAM CONTROLS

DELXI	DELXJ	DELXK	DELXIA	DELXIB
1.0000	0.9714	4.8378	10.0000	5.0000
SIGLIM	SLIM	WRTSKP	PFEXP	PFEND
5.00	241.8894	4.	0.10000E-01	0.20000E-01
XJA	XJB	XJKCON	XJKINC	
10.	5.	6.	20.	

KEY

K1	K2	K3	K4	K5
1	13	21	31	41

FIGURE A-5. WITH ANALYTICAL ERROR - NO TEST

CASE 5

OUTPUT DATA

XI	PELXI	STRDNF	DELPF	PF
25.50	0.999997E 00	0.13838E-03	0.13838E-03	0.00108559
29.50	0.999993E 00	0.19721E-03	0.19720E-03	0.00178234
33.50	0.999979E 00	0.26865E-03	0.26864E-03	0.00274570
37.50	0.999942E 00	0.35341E-03	0.35339E-03	0.00402718
41.50	0.999848E 00	0.45217E-03	0.45210E-03	0.00568306
45.50	0.999625E 00	0.56554E-03	0.56533E-03	0.00776991
49.50	0.999105E 00	0.69411E-03	0.69349E-03	0.01034684
53.50	0.997967E 00	0.83847E-03	0.83677E-03	0.01347428
57.50	0.995655E 00	0.99913E-03	0.99479E-03	0.01721195
61.50	0.991273E 00	0.11766E-02	0.11663E-02	0.02161626
65.50	0.983483E 00	0.13714E-02	0.13488E-02	0.02673510
69.50	0.970319E 00	0.15840E-02	0.15370E-02	0.03259979
73.50	0.949273E 00	0.18149E-02	0.17228E-02	0.03921412
77.50	0.917739E 00	0.20644E-02	0.18946E-02	0.04654128
81.50	0.873438E 00	0.23331E-02	0.20379E-02	0.05443974
85.50	0.814876E 00	0.26214E-02	0.21361E-02	0.06290358
89.50	0.741794E 00	0.29296E-02	0.21732E-02	0.07156092
93.50	0.655865E 00	0.32582E-02	0.21369E-02	0.08018655
97.50	0.560926E 00	0.36075E-02	0.20236E-02	0.08847517
101.50	0.463512E 00	0.39779E-02	0.18438E-02	0.09614098
105.50	0.367265E 00	0.43699E-02	0.16049E-02	0.10293037
109.50	0.278676E 00	0.47837E-02	0.13331E-02	0.10867506
113.50	0.202047E 00	0.52197E-02	0.10546E-02	0.11331016
117.50	0.139796E 00	0.56783E-02	0.79381E-03	0.11686891
121.50	0.920750E-01	0.61598E-02	0.56717E-03	0.11946368
125.50	0.575877E-01	0.66645E-02	0.38380E-03	0.12125844
129.50	0.341318E-01	0.71928E-02	0.24550E-03	0.12243515
133.50	0.191639E-01	0.77448E-02	0.14842E-03	0.12316483
137.50	0.102898E-01	0.83206E-02	0.85451E-04	0.12359262
141.50	0.520596E-02	0.89197E-02	0.46436E-04	0.12382931
145.50	0.248150E-02	0.95401E-02	0.23674E-04	0.12395298

THE FACTOR OF SAFETY FOR CASE 5 IS 1.500

THIS CASE ASSUMES THAT THE DESIGN IS BASED ON ANALYSIS ALONE WITH NO STRENGTH TEST REQUIRED.

THE STRUCTURAL RELIABILITY OF CASE 5 IS 0.87604702

FIGURE A-5. (Concluded)

CASE 6

INPUT DATA

STRUCTURES

AMUT	GAUS	TESTES	ULTTST	SIGALL
179.2774	0.0700	1.0000	150.0000	2.3263
FS	MS	DF	DSGNLD	MTEST
1.500	0.0	1.000	150.0000	1
ACFAC				
1.00				

LOADS

AMUL	GAML	LIMLD	ULTLD
100.000	0.16181	100.00000	150.00000

PROGRAM CONTROLS

DELXI	DELXJ	DELXK	DELXIA	DELXIB
1.0000	0.9714	4.8378	10.0000	5.0000
SIGLIM	SLIM	WRTSKP	PFEXP	PFEND
5.00	241.8894	4.	0.10000E-04	0.10000E-02
XJA	XJB	XJKCON	XJKINC	
10.	5.	6.	20.	

KEY

K1	K2	K3	K4	K5
1	13	22	31	41

FIGURE A-6. WITH ANALYTICAL ERROR - ONE TEST (Y_a = 0.07)

CASE 6

OUTPUT DATA

XI	PELXI	STRDNF	DELPF	PF
80.50	0.885844E 00	0.51571E-08	0.45584E-08	0.00000001
84.50	0.830927E 00	0.31724E-07	0.26360E-07	0.00000007
88.50	0.761245E 00	0.15045E-06	0.11453E-06	0.00000036
92.50	0.678267E 00	0.55690E-06	0.37773E-06	0.00000140
96.50	0.585133E 00	0.16451E-05	0.96258E-06	0.00000426
100.50	0.488034E 00	0.40400E-05	0.19717E-05	0.00001049
104.50	0.390630E 00	0.88577E-05	0.34601E-05	0.00002192
108.50	0.299646E 00	0.19083E-04	0.57180E-05	0.00004108
112.50	0.219932E 00	0.43190E-04	0.94988E-05	0.00007279
116.50	0.154024E 00	0.10134E-03	0.15609E-04	0.00012527
120.50	0.102651E 00	0.23292E-03	0.23910E-04	0.00020793
124.50	0.649874E-01	0.50210E-03	0.32630E-04	0.00032570
128.50	0.390927E-01	0.99645E-03	0.38954E-04	0.00047348
132.50	0.223525E-01	0.18139E-02	0.40545E-04	0.00063504
136.50	0.121079E-01	0.30386E-02	0.36792E-04	0.00078881
140.50	0.618591E-02	0.47130E-02	0.29154E-04	0.00091709
144.50	0.297530E-02	0.68167E-02	0.20282E-04	0.00101149
148.50	0.135083E-02	0.92626E-02	0.12512E-04	0.00107317
152.50	0.586329E-03	0.11909E-01	0.69823E-05	0.00110913
156.50	0.244437E-03	0.14579E-01	0.35636E-05	0.00112790
160.50	0.947821E-04	0.17083E-01	0.16191E-05	0.00113670
164.50	0.341136E-04	0.19225E-01	0.65583E-06	0.00114047
168.50	0.114400E-04	0.20809E-01	0.23806E-06	0.00114194
172.50	0.362792E-05	0.21650E-01	0.78545E-07	0.00114246
176.50	0.114381E-05	0.21596E-01	0.24701E-07	0.00114263
177.50	0.812261E-06	0.21431E-01	0.17408E-07	0.00114265

THE FACTOR OF SAFETY FOR CASE 6 IS 1.500

THE PROBABILITY OF AT LEAST ONE TEST FAILURE AT LIMIT LOAD OR LESS DURING THE SPECIFIED STRENGTH TEST IS 0.105

THE PROBABILITY OF AT LEAST ONE TEST FAILURE AT ULTIMATE TEST LOAD OR LESS DURING THE SPECIFIED STRENGTH TEST IS 0.390

AFTER ALL TEST DISCREPANCIES ARE CORRECTED AND THE STRUCTURE HAS SUCCESSFULLY PASSED THE SPECIFIED STRENGTH TEST, THE STRUCTURAL RELIABILITY OF CASE 6 IS 0.99985738

FIGURE A-6. (Concluded)

CASE 7

INPUT DATA

STRUCTURES

AMUT	GAMS	TESTFS	ULTTST	SIGALL
339.0000	0.2400	1.0000	150.0000	2.3263

FS	MS	DF	DSGNLD	NTEST
1.500	0.0	1.000	150.0000	1

ACFAC
1.00

LOADS

AMUL	GAML	LIMLD	ULTLD
100.000	0.16181	100.00000	150.00000

PROGRAM CONTROLS

DELXI	DELXJ	DELXK	DELXIA	DELXIB
1.0000	3.0005	14.9427	10.0000	5.0000

SIGLIM	SLIM	WRTSKP	PFEXP	PFEND
5.00	747.1326	10.	0.10000E-03	0.10000E-02

XJA	XJB	XJKCON	XJKINC
10.	5.	6.	20.

KEY

K1	K2	K3	K4	K5
1	13	22	31	41

FIGURE A-7. WITH ANALYTICAL ERROR - ONE TEST (Y_a = 0.24)

CASE 7

OUTPUT DATA

XI	PELXI	STRONF	DELPF	PF
0.50	0.100000E 01	0.11104E-05	0.11104E-05	0.00000111
10.50	0.100000E 01	0.22654E-05	0.22654E-05	0.00001788
20.50	0.999999E 00	0.46661E-05	0.46661E-05	0.00005250
30.50	0.999984E 00	0.96306E-05	0.96305E-05	0.00012334
40.50	0.999774E 00	0.19643E-04	0.19639E-04	0.00026911
50.50	0.998998E 00	0.38896E-04	0.38857E-04	0.00056137
60.50	0.991566E 00	0.73611E-04	0.72990E-04	0.00112261
70.50	0.962644E 00	0.13189E-03	0.12697E-03	0.00213391
80.50	0.885565E 00	0.22282E-03	0.19732E-03	0.00378227
90.50	0.709738E 00	0.35454E-03	0.25163E-03	0.00608472
100.50	0.495890E 00	0.53203E-03	0.26383E-03	0.00871457
110.50	0.259037E 00	0.75548E-03	0.19570E-03	0.01104950
120.50	0.108026E 00	0.10200E-02	0.11018E-03	0.01253122
130.50	0.298938E-01	0.13165E-02	0.39355E-04	0.01320466
140.50	0.711754E-02	0.16339E-02	0.11629E-04	0.01343678
150.50	0.130894E-02	0.19605E-02	0.25661E-05	0.01348427
160.50	0.980377E-04	0.22856E-02	0.22408E-06	0.01349396
170.50	0.143559E-04	0.26004E-02	0.37332E-07	0.01349514
171.50	0.699563E-05	0.26311E-02	0.18406E-07	0.01349515

THE FACTOR OF SAFETY FOR CASE 7 IS 1.500

THE PROBABILITY OF AT LEAST ONE TEST FAILURE AT LIMIT LOAD OR LESS DURING THE SPECIFIED STRENGTH TEST IS 0.049

THE PROBABILITY OF AT LEAST ONE TEST FAILURE AT ULTIMATE TEST LOAD OR LESS DURING THE SPECIFIED STRENGTH TEST IS 0.105

AFTER ALL TEST DISCREPANCIES ARE CORRECTED AND THE STRUCTURE HAS SUCCESSFULLY PASSED THE SPECIFIED STRENGTH TEST, THE STRUCTURAL RELIABILITY OF CASE 7 IS 0.98650485

FIGURE A-7. (Concluded)

REFERENCES

1. Pugsley, A. G. A Philosophy of Aeroplane Strength Factors. ARC R&M No. 1906 (September 1942).

2. Draper, C. S. "The Role of Informatics in Modern Flight Systems," presented as Preprint 66-131 at the AIAA 3rd Aerospace Sciences Meeting, New York (January 24-26, 1966). Published in Journal of Spacecraft and Rockets, Vol. 3, No. 6 (June 1966).

3. Bouton, Innes. The Implementation of Reliability Concepts in Structural Design Criteria, presented at International Council of the Aeronautical Sciences, Paris, France, as AIAA Paper No. 64-571 (August 1964).

4. Bouton, Innes, D. J. Trent, and H. B. Chenoweth. Deterministic Structural Design Criteria Based on Reliability Concepts, AIAA Preprint 66-504, presented at the AIAA Fourth Aerospace Sciences Meeting, Los Angeles, California (28 June 1966).

5. Bouton, Innes, D. J. Trent, and H. B. Chenoweth. "Design Factors for Structural Reliability." NAA S&ID, SID 65-874. Presented at AIAA/SAE/ASME Fifth Reliability and Maintainability Conference, New York, New York (18 July 1966). Published in Annals of Reliability and Maintainability, Volume 5 (July 1966), pp. 229-235.

6. Bouton, Innes and D. J. Trent. Further Analysis of the Design Factors and Test Factors Required for a Specified Structural Reliability. NAA S&ID, Internal Report LCM 66-63 (February 1966).

7. Trent, D. J. A Study of Procedures for Disclosing Errors in Loads Analyses. NAA S&ID, Internal Report LCM 65-52 (August 1965).

8. Bouton, Innes. Preliminary Results from Computer Program Determining the Effects of Structural Design Factors on Structural Reliability. NAA S&ID, Internal Report LCM 65-44 (July 1965).

9. Readey, W. B. An Investigation of the Definition of Missile Structural Design Criteria Requirements on a Reliability Basis. Part II. The Development of a Method Framework for Determining the Quantitative Structural Requirements Necessary to Achieve a Given Level of Structural Reliability. WADD TR 60-556, Part II (August 1960).

10. Landes, P. E., R. E. Wagner and W. A. Kriegshauser. An Investigation of the Definition of Missile Structural Design Requirements on a Reliability Basis. Part I. The Integration of Current Data into Recommended Requirements. WADD TR 60-556, Part I (August 1960). Confidential

11. Kluger, P. "Prediction of Design Reliability of Very Large Solid-Rocket Motors," Journal of Spacecraft and Rockets, Vol. 1 (March-April 1964), pp. 139-142.

12. Haire, E. T. "Titan II Structures Reliability Analysis," Proceedings of the Sixth Symposium on Ballistic Missile and Aerospace Technology, Volume I, pp. 275-302.

13. Lundberg, Bo K. O. Speed and Safety in Civil Aviation. Part II: Safety. Report 95, Aeronautical Research Institute of Sweden, Stockholm, Sweden (1963).

14. Diederich, F. W., W. C. Broding, A. J. Hanawalt and R. Sirull. "Reliability as a Thermostructural Design Criterion," Transactions of the Seventh Symposium on Ballistic Missile and Space Technology, Volume I (1962), pp. 493-536.

15. Freudenthal, A. M. and A. O. Payne. The Structural Reliability of Airframes. AFML TR-64-401 (1964).

16. Coutinho, John De S. and Bernard Tiger. "Achieving System Effectiveness Through Reliability Prediction — 1966 Review —." Annals of Reliability and Maintainability, Volume 5. AIAA (1966), pp. 678-685.

17. Jablecki, L. S. Analysis of the Premature Structural Failures in Static Tested Aircraft. Zurich: Leeman (1955).

18. Report on Statistical Maneuver Loads Research. Papers from a Special Panel of the NACA Subcommittee on Aircraft Loads (June 1954).

19. Stieglitz, William I. "Numerical Safety Goals--Are They Practicable?" Annals of Reliability and Maintainability, Volume 5 (July 1966), pp. 490-493.

20. Military Specification: Airplane Strength and Rigidity, Flight Loads. MIL-A-8861 (ASG)(18 May 1960).

21. Bouton, Innes, D. J. Trent and H. B. Chenoweth. Objectives and Application of Structural Design Factors for Space Vehicles. NAA S&ID, SID 65-486 (March 1965).

22. Serling, Robert S. The Electra Story. New York: Doubleday (1963).

23. Military Specification: Airplane Strength and Rigidity, General Specification for, MIL-A-8860 (ASG)(18 May 1960).

24. McLaughlin, H. D. Comments on A. M. Freudenthal's Paper Entitled "Life Estimate of Fatigue Sensitive Structures." NAA S&ID, Internal Report LCM 65-57 (October 1965).

25. McLaughlin, H. D. The Effect of Correlated Loads on the Probability that a Structure of Several Parts Survives. NAA S&ID, Internal Report LCM 66-72 (December 1966).

26. Grose, V. L. "Reliability Can be Predicted? (A Negative Position)," Annals of Reliability and Maintainability, Volume 4 (July 1965), pp. 119-129.

27. Rhode, R. V. Private Communication (1963).

28. Wagner, R. E. Guided Missile Structural Design Criteria: A Modified Safety Factor Approach. ARS Preprint 2403-62 (April 1962).

29. Austin, W. H., Jr. Application of a Rational-Probability Analysis for Determination of Ultimate Design Loads in Large Flexible Military Aircraft. SEG TDR-64-24 (May 1964).

30. Austin, W. H., Jr. Environmental Conditions to be Considered in the Structural Design of Aircraft Required to Operate at Low Levels. SEG TR-65-4 (January 1965).

31. Austin, W. H., Jr. The Effects of Low-Level Turbulence on the Structure of a Large Logistic Aircraft. SAE Preprint 660670 (October 1966).

32. Rice, S. O. "Mathematical Analysis of Random Noise," Bell System Technical Journal, Vol. XXII, No. 3 (July 1944), pp. 282-332, and Vol. XXIV, No. 1 (January 1945), pp. 46-156.

33. Hamer, H. A., J. P. Mayer and W. B. Huston. Application of Monte Carlo Technique for Determining Maneuvering Loads from Statistical Information on Airplane Motions. NASA TN D-524 (May 1961).

34. Coutinho, John de S. A History of Selected Reliability and Maintainability Committees and Interested Government Agencies. AIAA Paper 66-856 (December 1966).

35. Taylor, James. Manual on Aircraft Loads. Oxford: Pergamon Press (1965).

36. Christenson, C. M. "Designing for Airline Safety," Aerospace Engineering (September 1962).

37. Lundberg, Bo K. O. "Fatigue Life of Airplane Structures," Journal of the Aeronautical Sciences, Vol. 22, No. 6 (June 1955), pp. 349-402.

38. Lundberg, Bo K. O. and Sigge Eggwertz. A Statistical Method for Fail-Safe Design with Respect to Aircraft Fatigue. Aeronautical Research Institute of Sweden, Report 99 (April 1964).

39. Lundberg, Bo K. O. Notes on the Level of Safety and the Repair Rate with Regard to Fatigue in Civil Aircraft Structures. Aeronautical Research Institute of Sweden, Technical Note HE-794 (1958).

40. Serling, Robert J. The Probable Cause.... New York: Doubleday & Company (1960).

41. Freudenthal, A. M. Fatigue Sensitivity and Reliability of Mechanical Systems, Especially Aircraft Structures. WADD TR 61-53 (July 1961).

42. Freudenthal, A. M. Life Estimate of Fatigue Sensitive Structures. ML TDR-64-300 (September 1964).

43. Freudenthal, A. M., W. Weibull and A. O. Payne. First Seminar on Fatigue and Fatigue Design. Technical Report No. 2, Columbia University Institute for the Study of Fatigue and Reliability (December 1963).

44. Freudenthal, A. M. and M. Shinozuka. Structural Safety Under Conditions of Ultimate Load Failure and Fatigue. WADD TR 61-177 (October 1961).

45. Freudenthal, A. M., J. M. Garrelts and M. Shinozuka. The Analysis of Structural Safety. Technical Report No. 12, Columbia University Institute for the Study of Fatigue and Reliability (October 1964).

46. Freudenthal, A. M. "Safety and the Probability of Structural Failure," Transactions of the American Society of Civil Engineers, Vol. 80 (1954), pp. 1337-1397.

47. "Mariner 3 Finding." Aviation Week and Space Technology, Vol. 81 (December 7, 1964), p. 26.

48. Broding, W. C., F. W. Diederich and P. S. Parker. "Structural Optimization and Design Based on a Reliability Design Criterion," Journal of Spacecraft, Vol. 1, No. 1 (January-February 1964), pp. 56-61.

49. Switzky, H. "Minimum Weight Design with Structural Reliability," AIAA Fifth Annual Structures and Material Conference, AIAA Publication CP-8 (April 1964), pp. 316-322.

50. Hilton, H. H. and M. Feigen. "Minimum Weight Analysis Based on Structural Reliability," Journal of the Aerospace Sciences, Vol. 27, No. 9 (September 1960), pp. 641-652.

51. Ghista, D. N. Structural Optimization with Probability of Failure Constraint. NASA TN D-3777 (December 1966).

52. Van der Neut, A. Some Remarks on the Fundamentals of Structural Safety. AGARD Report No. 155 (November 1957).

53. Bouton, Innes and D. J. Trent. Test Factor of Safety: A New Means for Proving Compliance with Structural Reliability Requirements. NAA S&ID, SID 66-1440 (January 1967). Presented at the AIAA 8th Structures, Structural Dynamics and Materials Conference, Palm Springs, California (30 March 1967).

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) North American Rockwell Corporation Los Angeles, California	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

Quantitative Structural Design Criteria by Statistical Methods, Volume I

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final report

5. AUTHOR(S) (Last name, first name, initial)

Bouton, Innes; Trent, D. J.

6. REPORT DATE June 1968	7a. TOTAL NO. OF PAGES 150	7b. NO. OF REFS 53
8a. CONTRACT OR GRANT NO. AF33(615)-3755	9a. ORIGINATOR'S REPORT NUMBER(S) North American Rockwell NA-67-40-1 and SID 67-495-1	
b. PROJECT NO. 1367		
c. Task 136714	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFFDL-TR-67-107 (Volume I)	
d.		

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Flight Dynamics Laboratory Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

Exploratory research, needed to develop quantitative structural design criteria for aerospace vehicles, has been conducted to relate the probabilistic nature of design, operational, and environmental experiences to the structural performance of aerospace vehicles. This design criteria is predicated on the concept of structural reliability. Volume I presents a critique of present and proposed approaches to structural design criteria. Volume II presents recommendations for a deterministic structural design criteria procedure based on statistical methods. This is a new procedure intended to overcome the problems associated with other structural design criteria procedures. The new procedure is demonstrated on the F-100 airplane by comparing the output of the computer program with actual service records. Volume III formulates two computer programs for the procedure and presents user's instructions for the programs.

The critique of Volume I concludes that none of the approaches in the literature today provides a satisfactory foundation for quantitative structural design criteria based on statistical methods.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Reliability						
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